The "Hot" (and "cold") Science of RHIC

Status and Future

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Associate Laboratory Director
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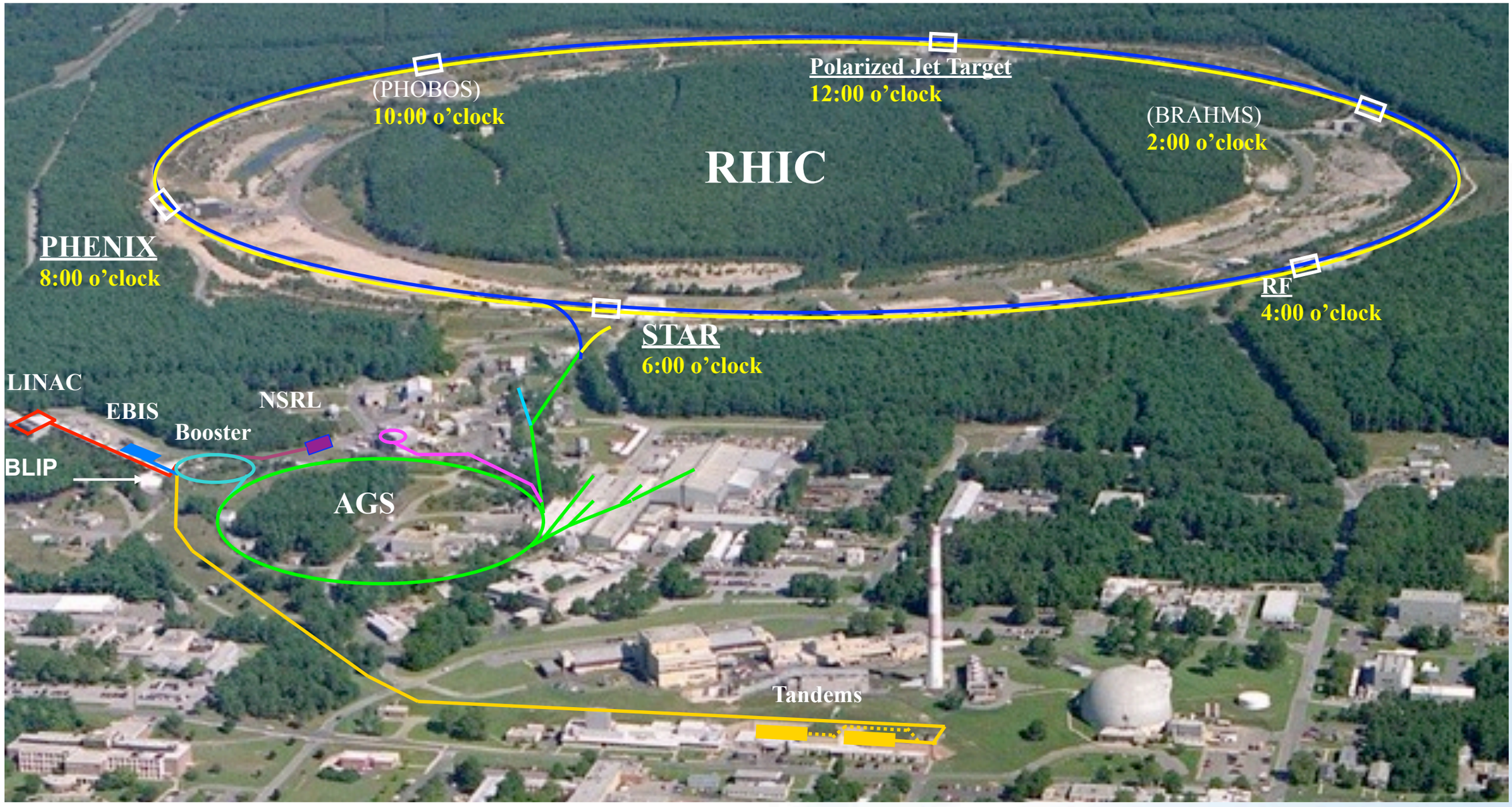
RHIC/AGS Users Meeting
BNL, 26 June 2013

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

RHIC: A Discovery Machine



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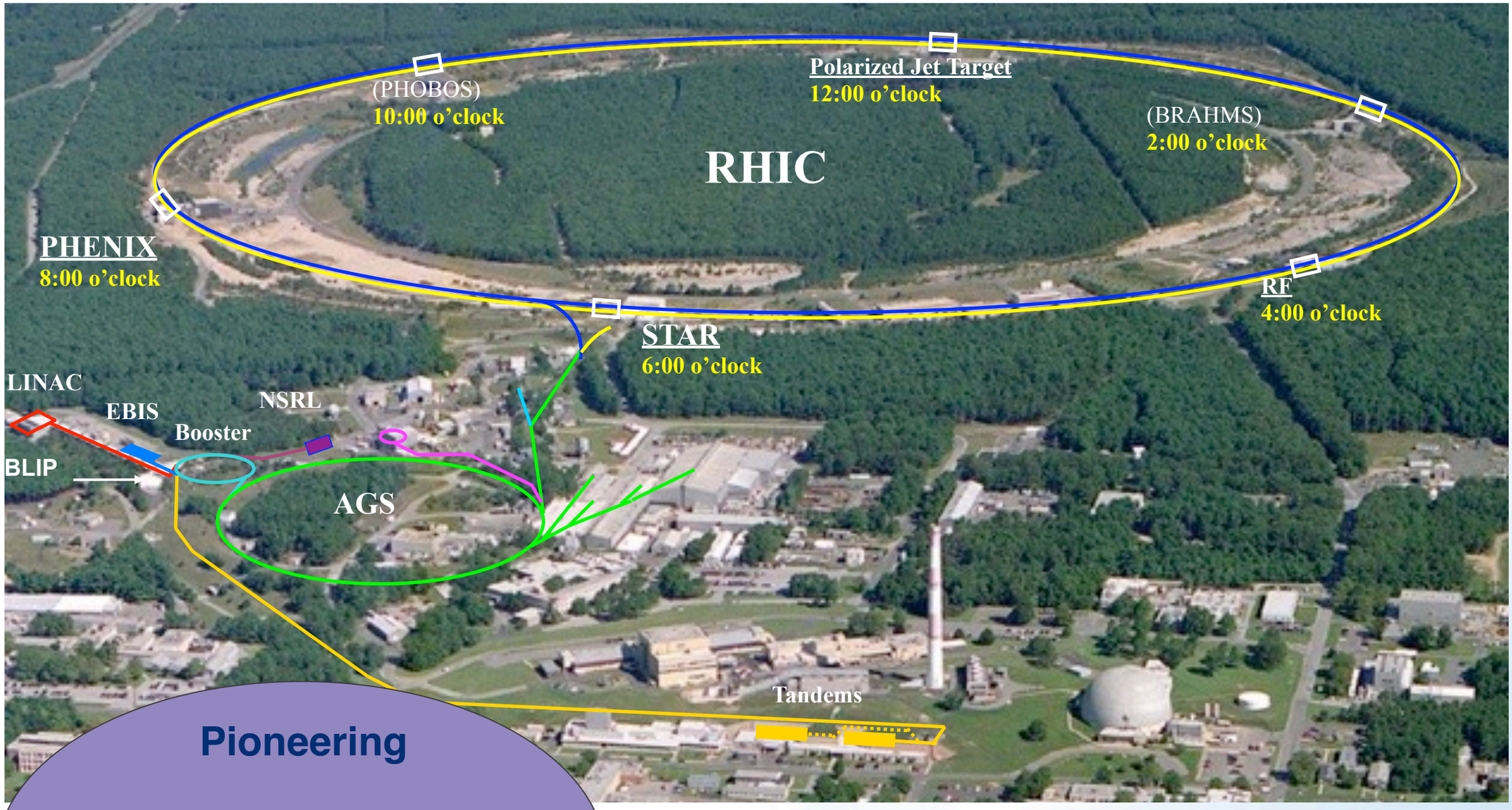
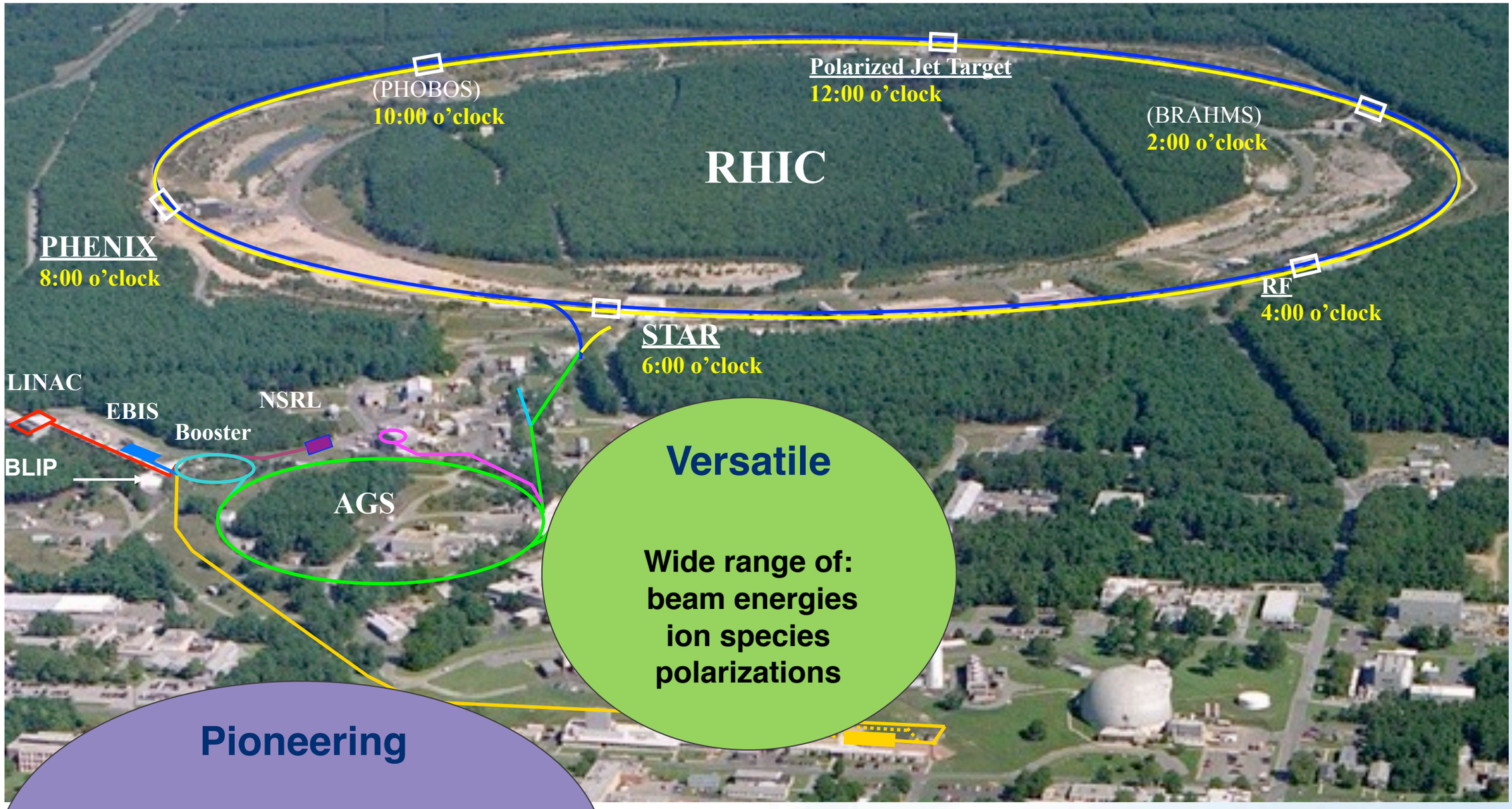


Pioneering

Perfectly liquid quark-gluon plasma; Polarized proton collider

RHIC: A Discovery Machine



Versatile

Wide range of:
beam energies
ion species
polarizations

Pioneering

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quark-gluon plasma;
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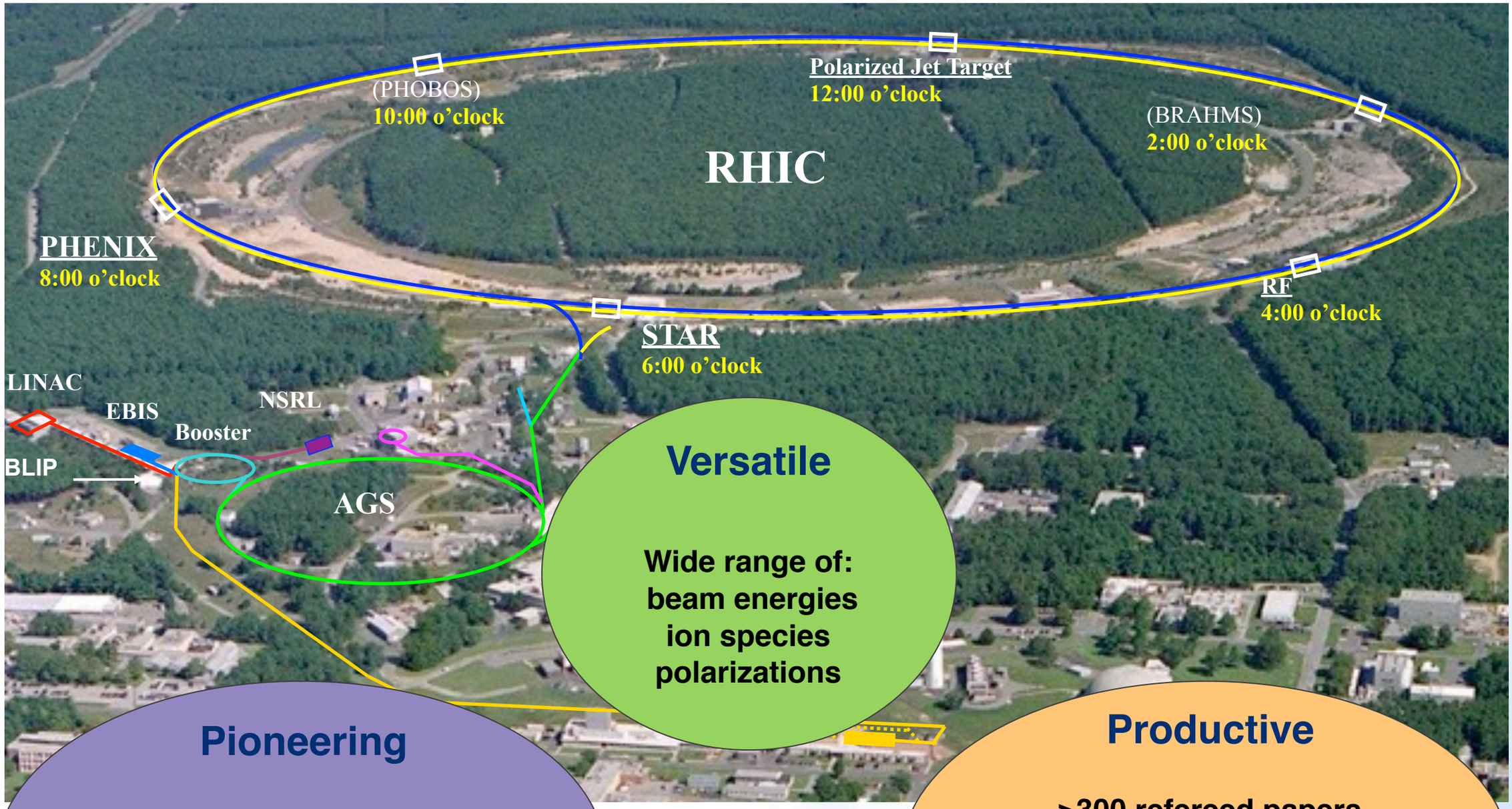

Versatile

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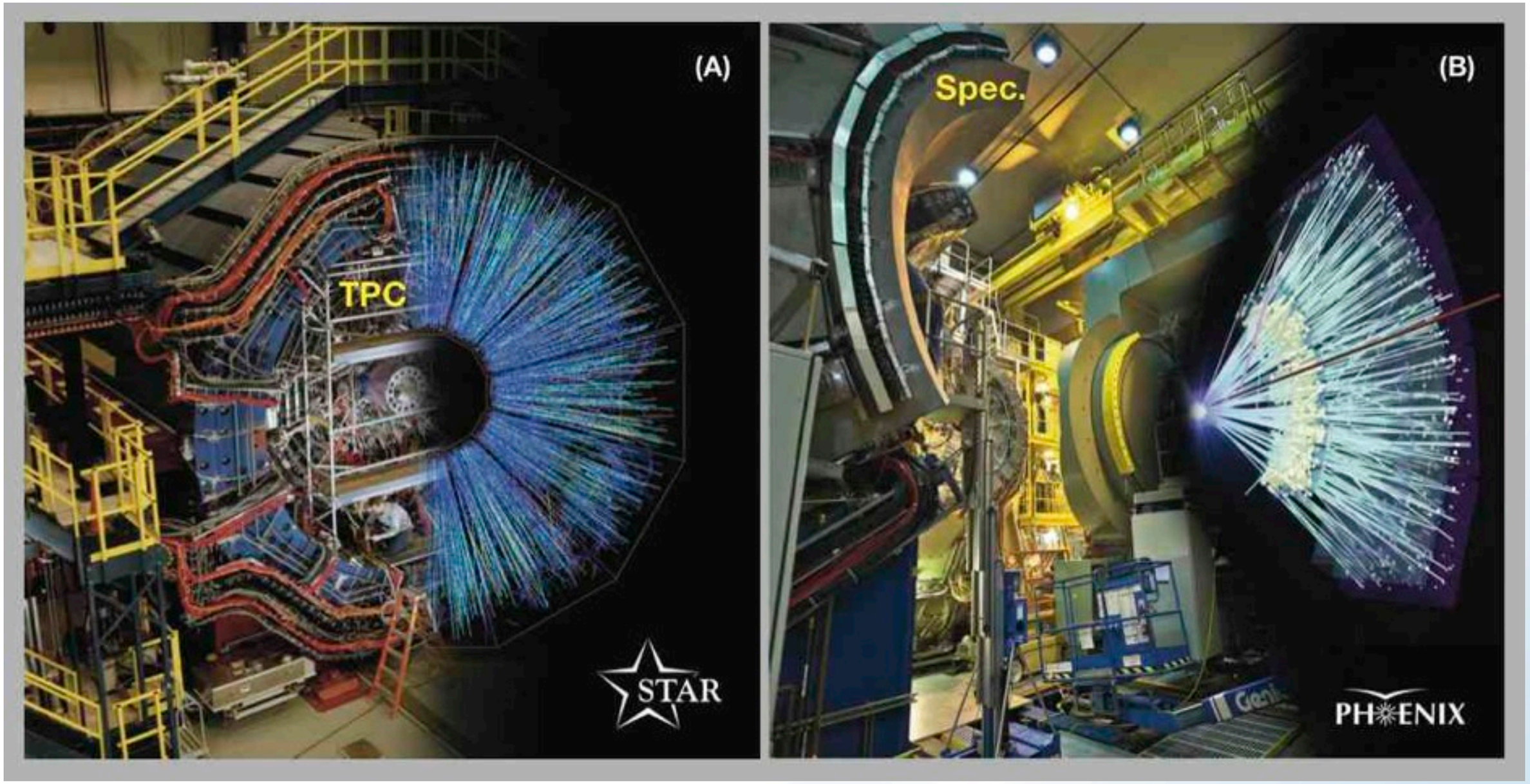
Productive

>300 refereed papers
>30k citations
>300 Ph.D.'s in 12 years
productivity still increasing

Detector Collaborations



559 collaborators from 12 countries

540 collaborators from 12 countries

RHIC explores the Phases of Nuclear Matter

LHC: High energy collider at CERN with 13.8 - 27.5 times higher beam energy: Pb+Pb, p+Pb, p+p collisions only.

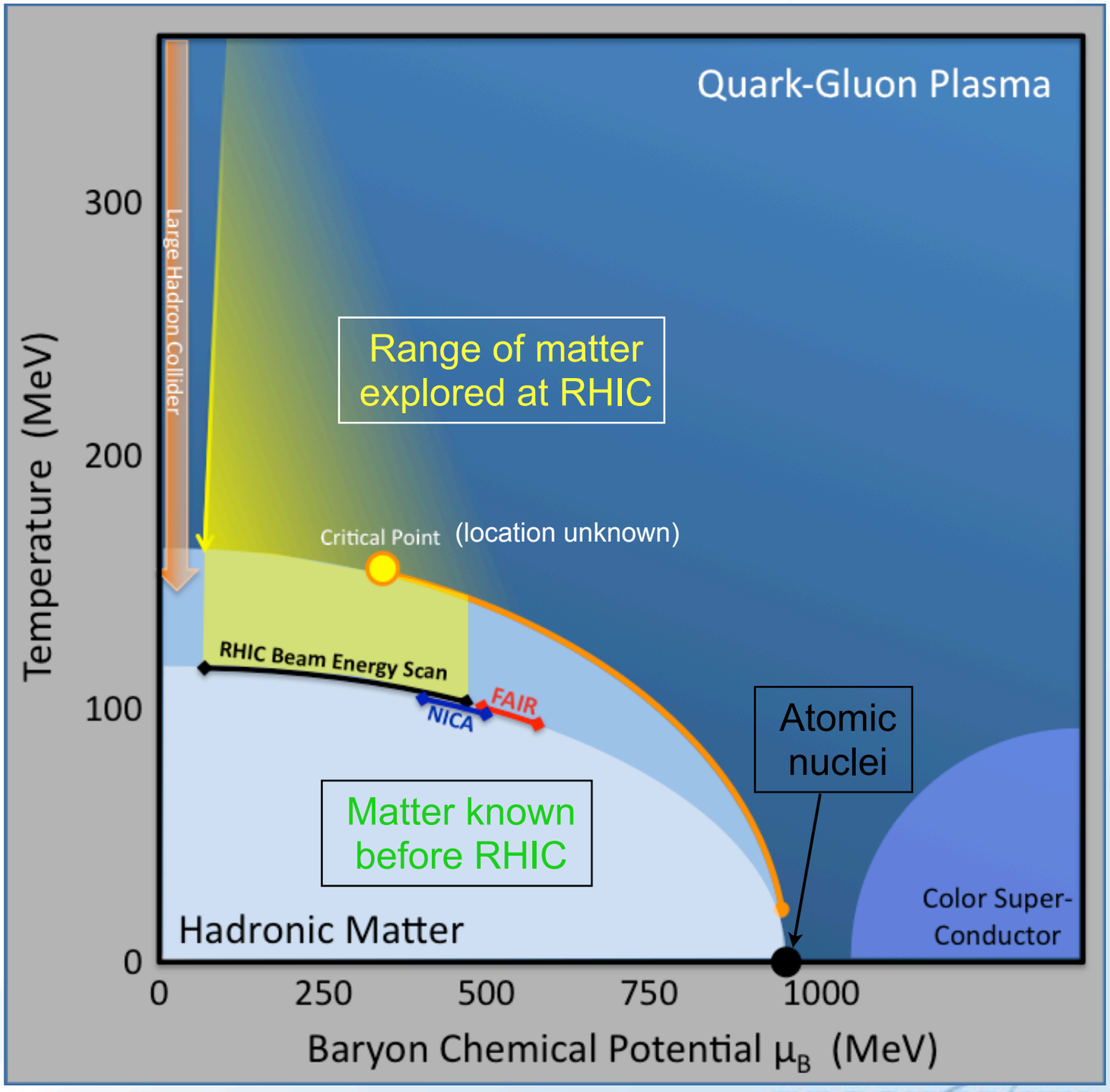
FAIR & NICA: Planned European facilities at lower energies.

RHIC: Spans largest swath of the phase diagram in preferred collider mode.

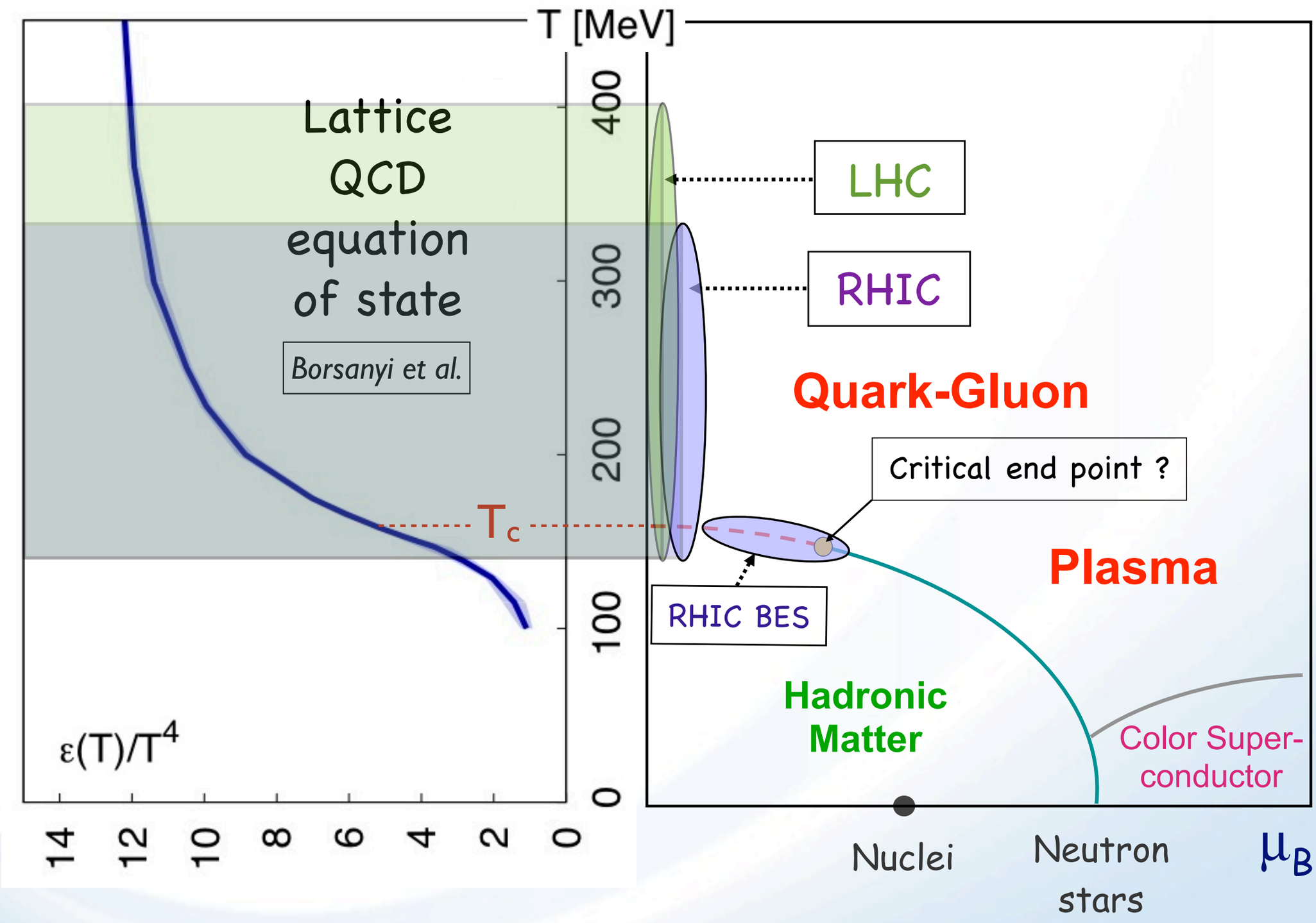
Message

RHIC is the perfect facility to explore the phases of nuclear (QCD) matter.

If RHIC did not exist, someone would have to build it (...but no one could afford it!)



QCD Phase Diagram



Quantum Chromo-Dynamics (QCD):
Fundamental theory of nuclear or “strong” interactions

Nuclei are really complex assemblies of quarks and gluons

➠ Nuclear matter in all its forms is known as “QCD matter”

RHIC has pioneered the laboratory study of condensed QCD matter

RHIC’s results have defined a new subfield of (nuclear) physics.

Scientists, from condensed matter physicists to string theorists, have taken note.

So what has RHIC discovered?

Imagine....

...heating a liquid (nuclear matter) until it turns into vapor (nucleon/hadron gas) at approximately 100 billion degrees.

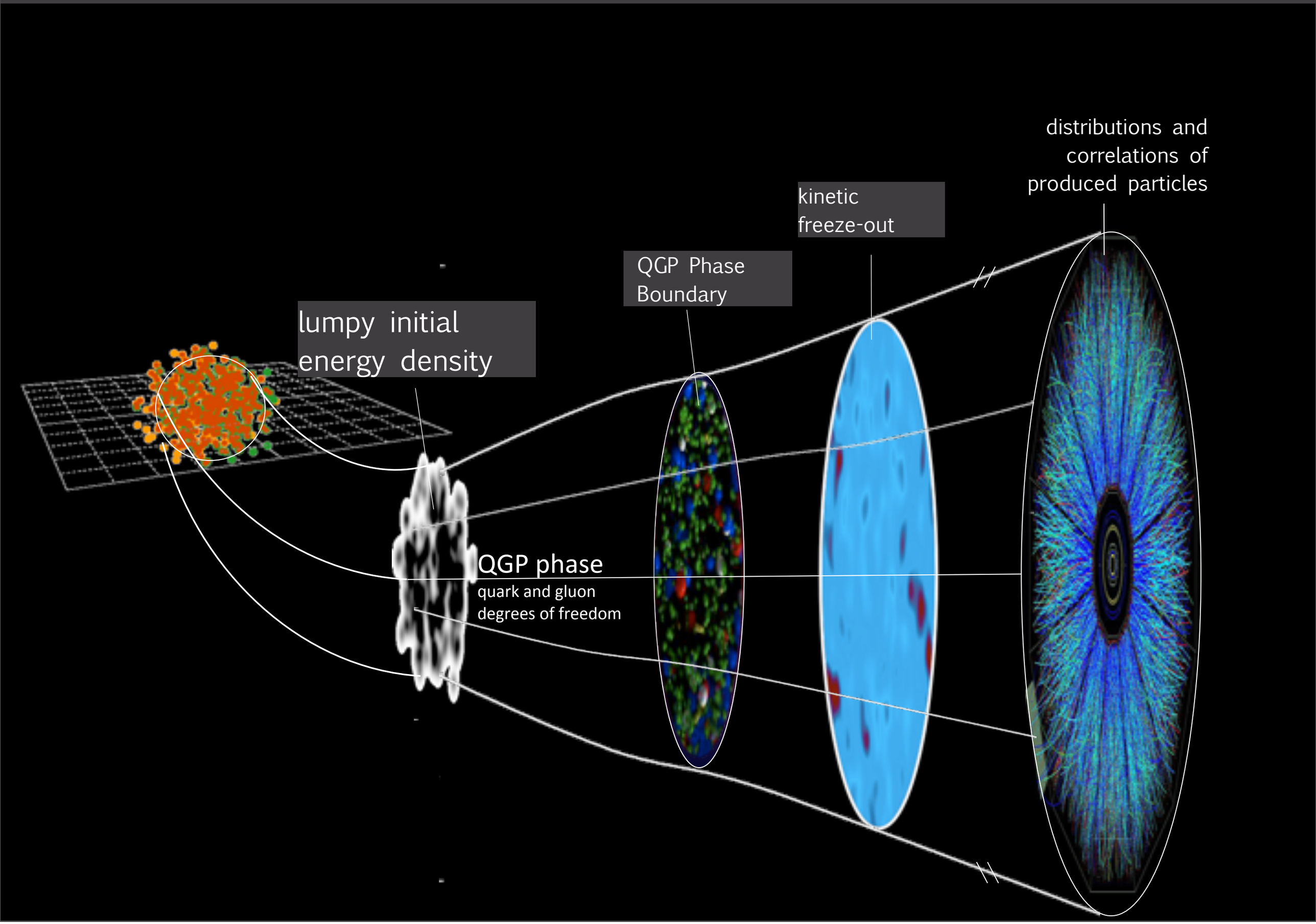
But when you heat it to 20 times this temperature (2 trillion degrees) you find that it suddenly turns into a **liquid** again, in fact, into the **most perfect liquid** ever observed.

How is this possible? [We don't really know.]

What happens at even higher temperatures? [We know.]

Where is the perfect liquid formed? [We almost know.]

RHIC has pioneered the lab study of condensed QCD Matter



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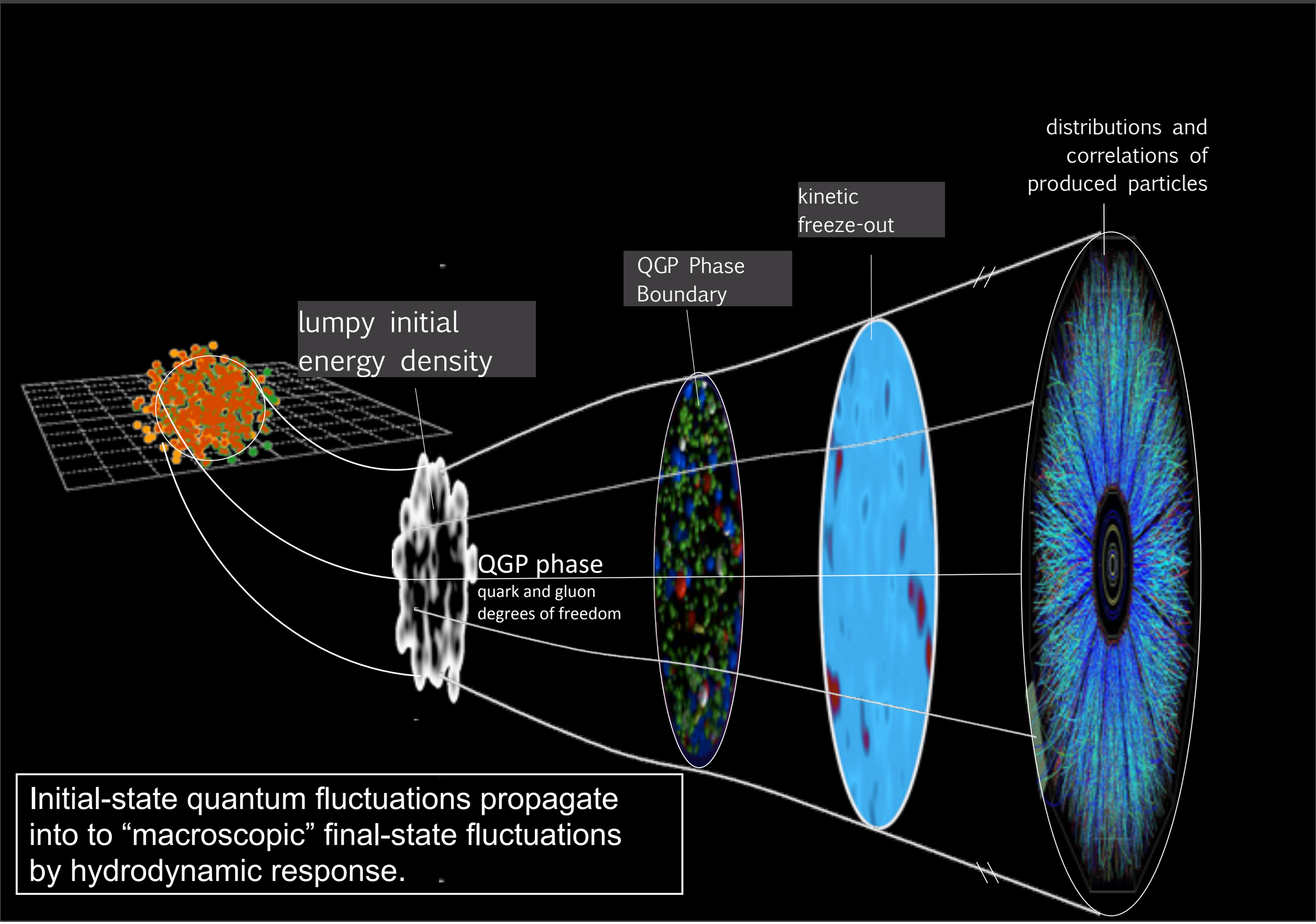


Initial-state quantum fluctuations propagate into to “macroscopic” final-state fluctuations by hydrodynamic response.

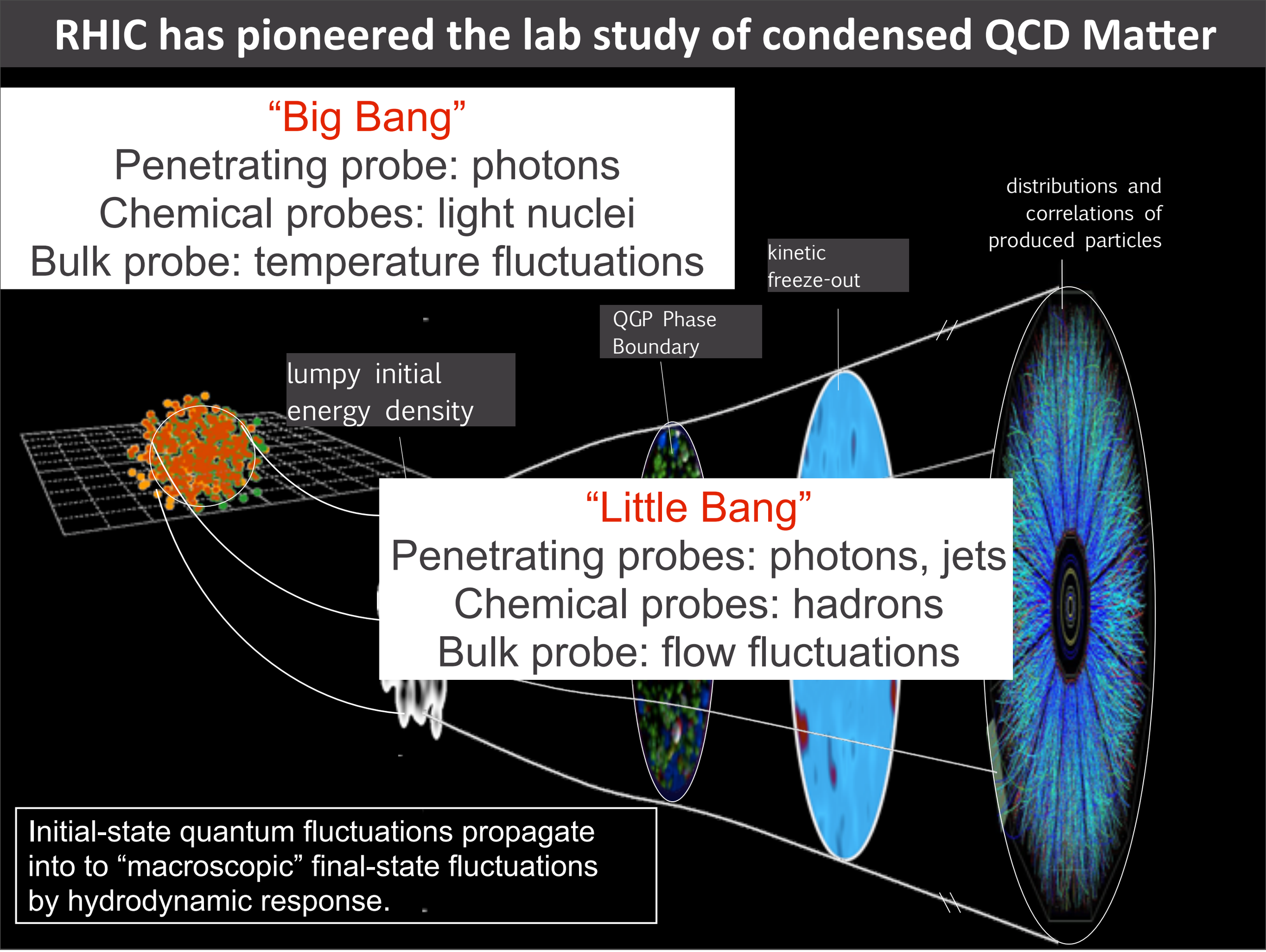
RHIC has pioneered the lab study of condensed QCD Matter

"Big Bang"

Penetrating probe: photons

Chemical probes: light nuclei

Bulk probe: temperature fluctuations



"Little Bang"

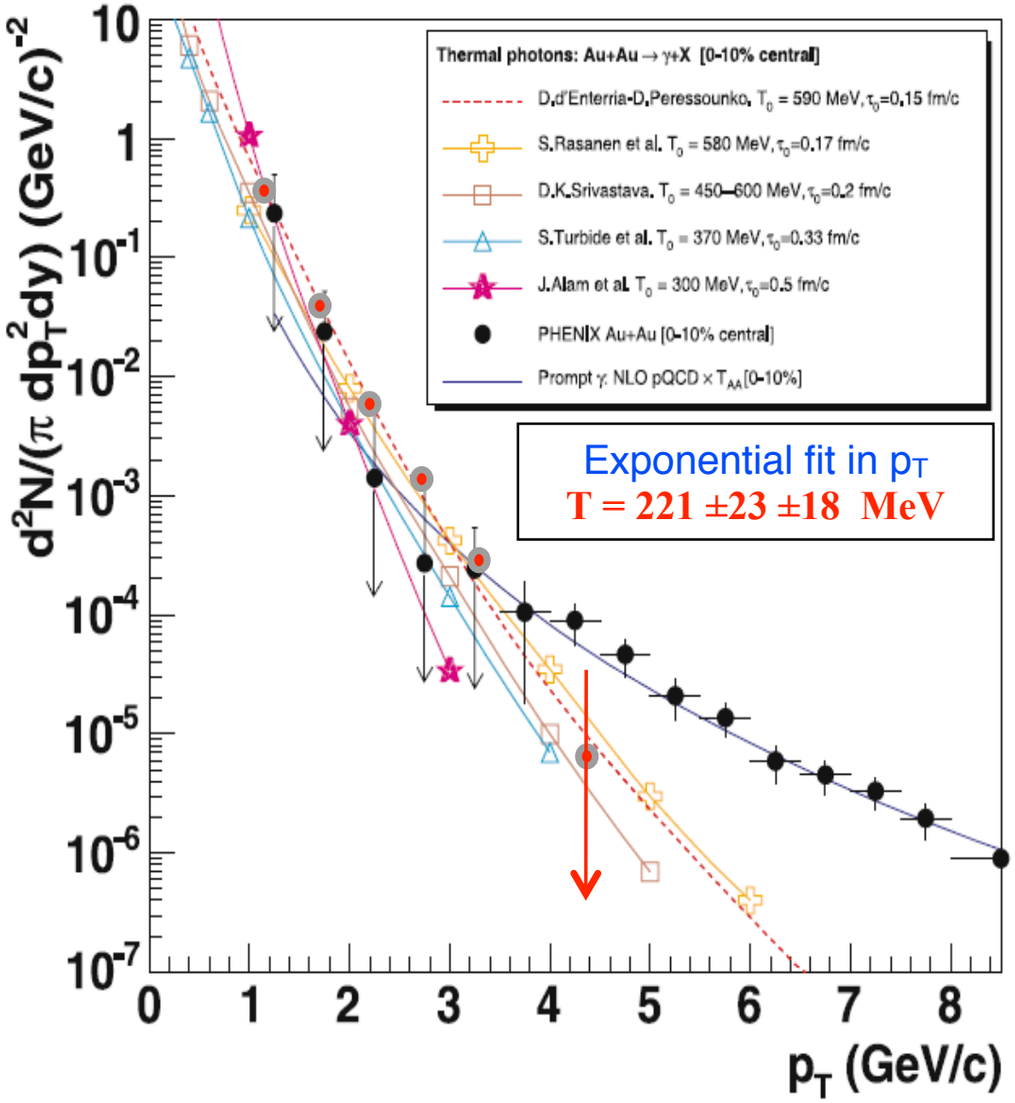
Penetrating probes: photons, jets

Chemical probes: hadrons

Bulk probe: flow fluctuations

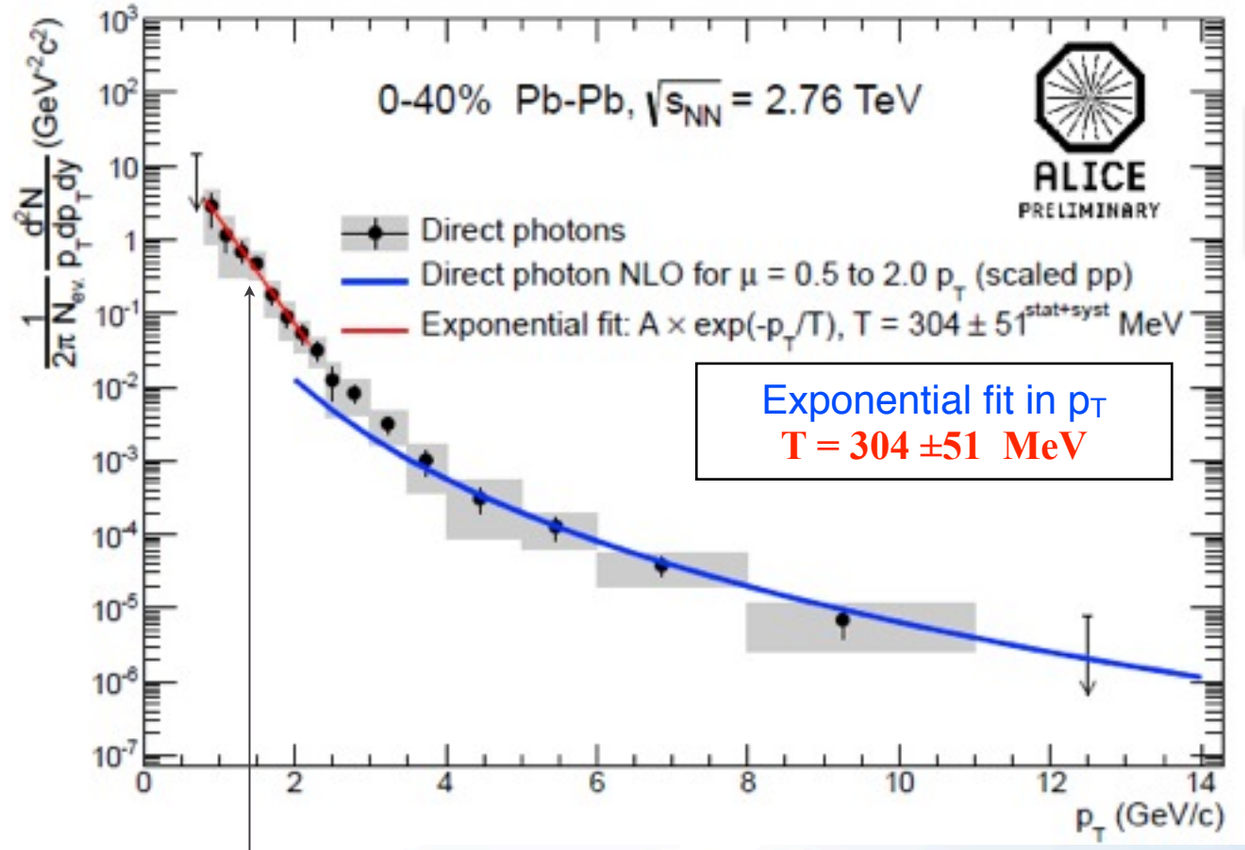
Initial-state quantum fluctuations propagate into to "macroscopic" final-state fluctuations by hydrodynamic response.

A "Guinness" record temperature



Exponential fit in p_T
T = 221 ±23 ±18 MeV

Corresponds to initial temperature:
$T_{init} \geq 300$ MeV



Exponential fit in p_T
T = 304 ±51 MeV

New **record "temperature"** measured at LHC:

$T_{LHC} = 1.37\ T_{RHIC}$

$T_{init} \geq 4$ trillion degrees

$T_{init} \geq 5.5$ trillion degrees

Measuring "fluidity"

Viscosity (η) measures how well a fluid responds to variations in the uniformity of flow.

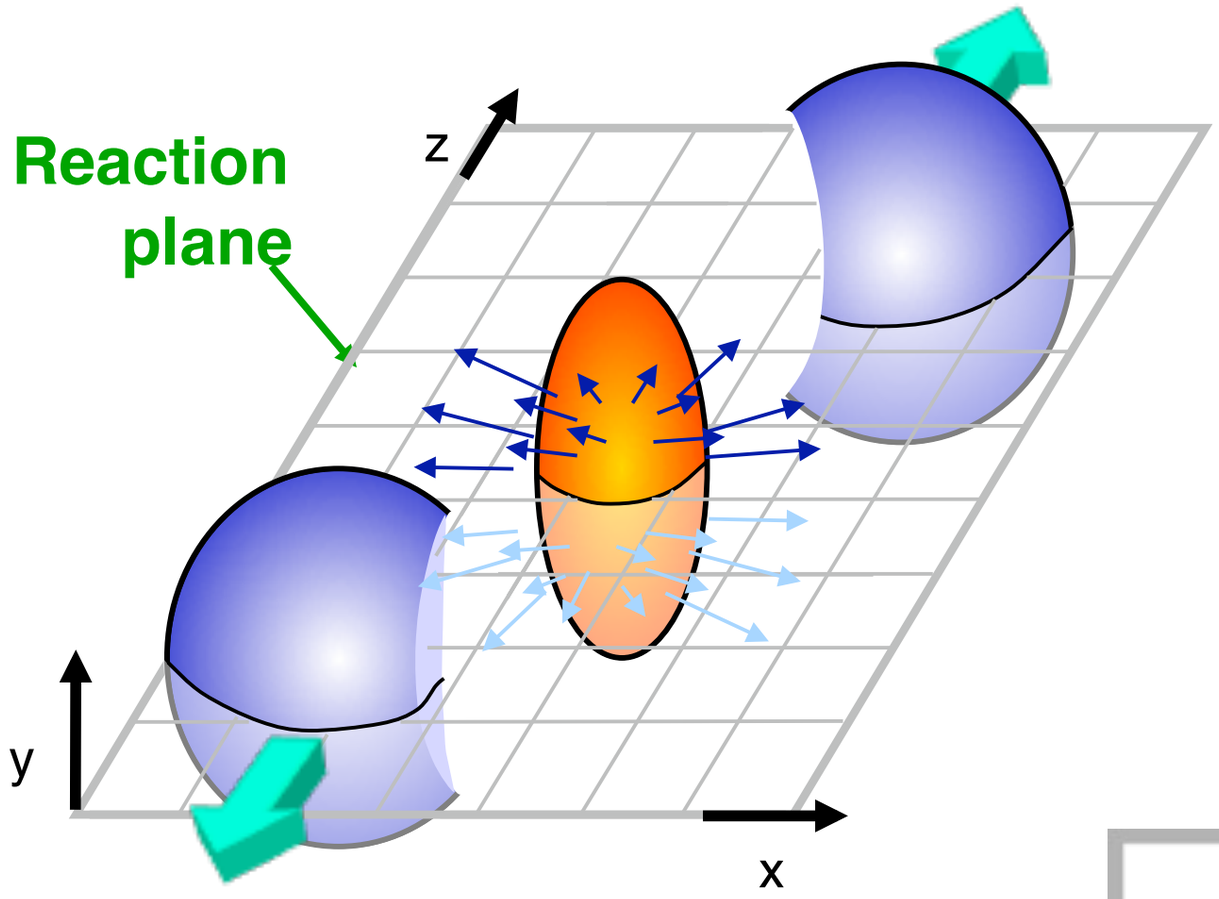
Quantum physics dictates that viscosity cannot be zero.

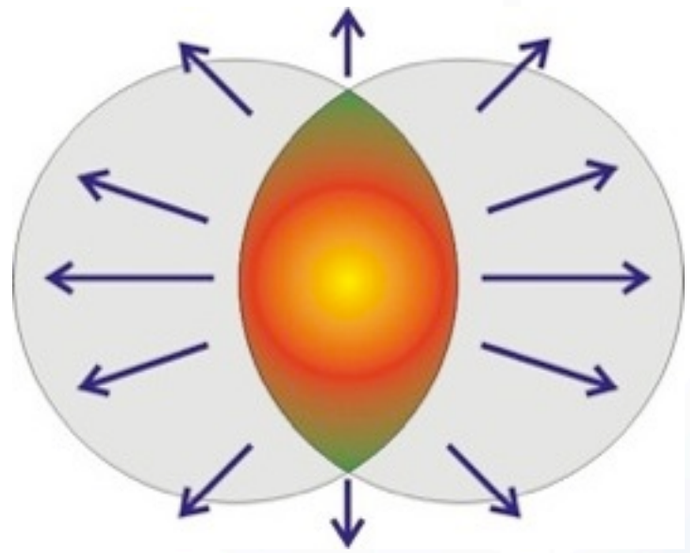
A dimensionless measure of perfect fluidity is η/s, which cannot be less than $1/4\pi \approx 0.08$.

The RHIC data indicate that QCD matter has $\eta/s \approx 0.12$.

No other liquid is known with such a low value.

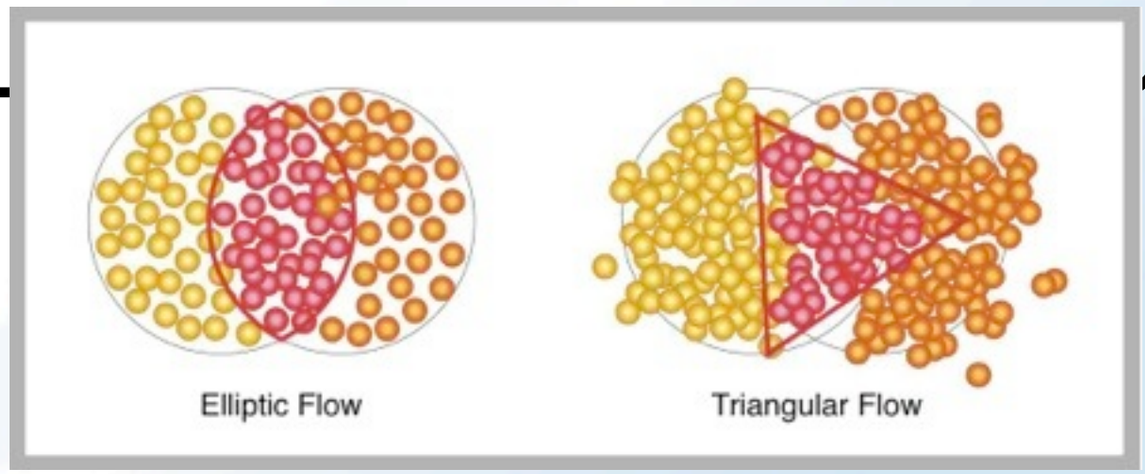
Anisotropic flow





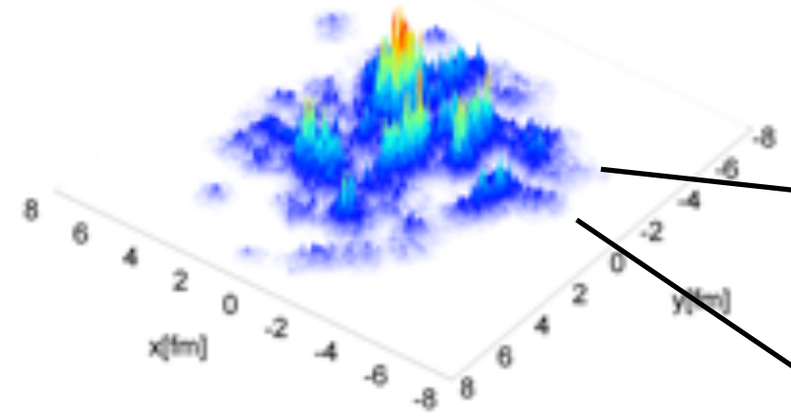
Only matter in the overlap area gets compressed and heated

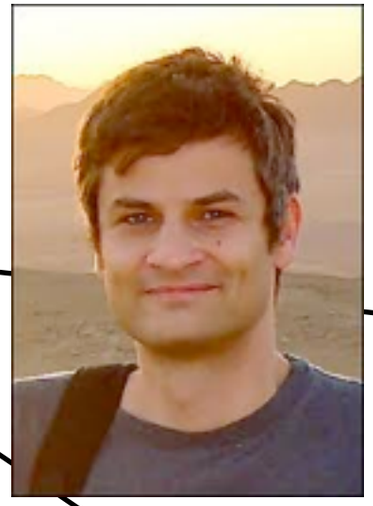
$$2\pi \frac{dN}{d\phi} = N_0 \left(1 + 2 \sum_n \mathrm{v}_n(p_T,\eta) \cos n\left(\phi - \psi_n(p_T,\eta)\right) \right)$$



QCD Matter at RHIC is most "perfect"

Initial density distribution



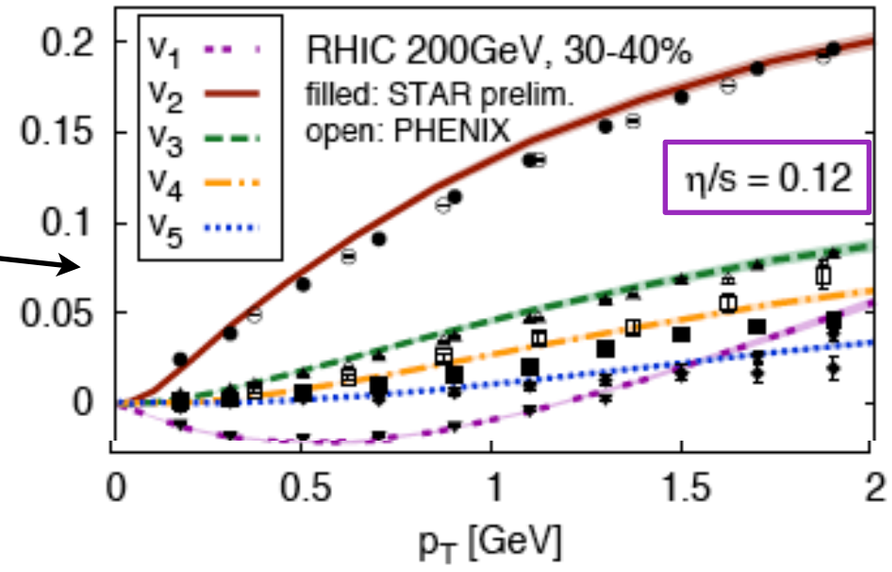


B. Schenke (BNL - Goldhaber Fellow)
IUPAP Young Scientist Award 2013

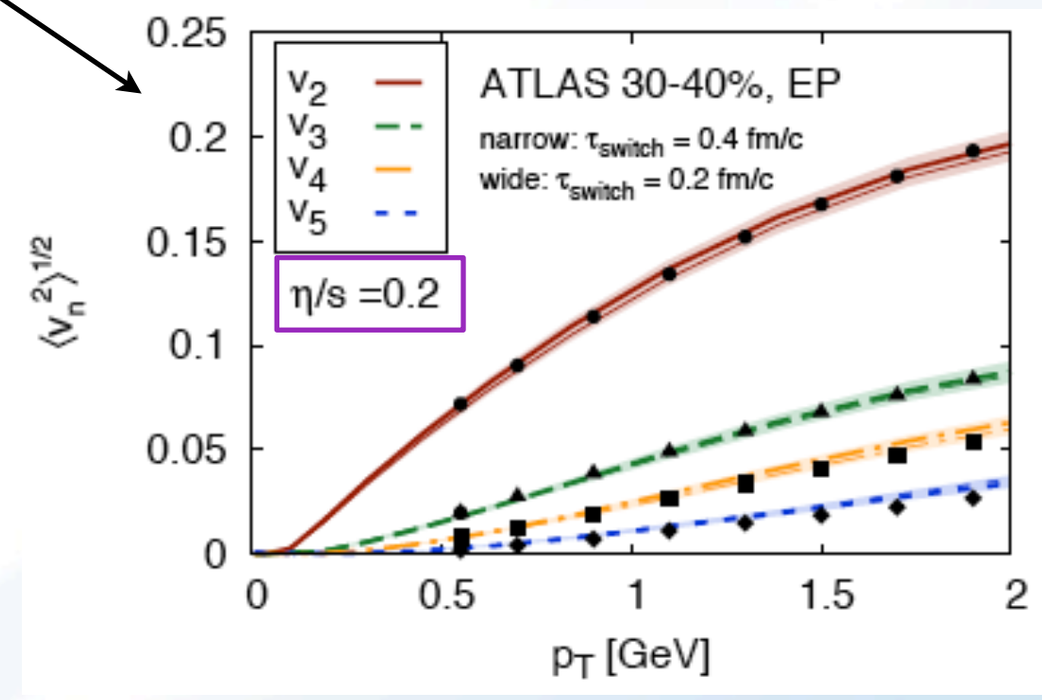
$(\eta/s)_{RHIC} \approx 0.6\ (\eta/s)_{LHC}$

A study of the opacity of the matter to energetic quarks (jets) confirms this conclusion:

QCD matter at RHIC is less transparent by the same factor 0.6.



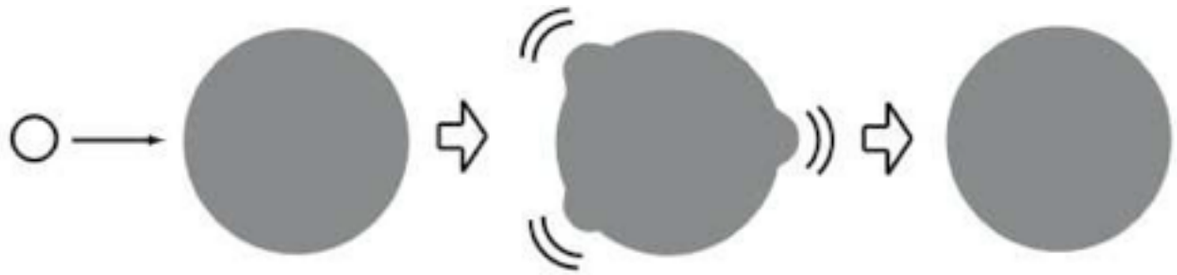
RHIC



LHC

The Black Hole connection

Dynamics of hot QCD matter can be mathematically mapped on black hole dynamics in 4 dimensions



BH swallowing matter

Perfect fluid hydrodynamics

Formation of hot QCD matter at RHIC is similar to formation of a black hole, tied to information loss.

The Black Hole connection II

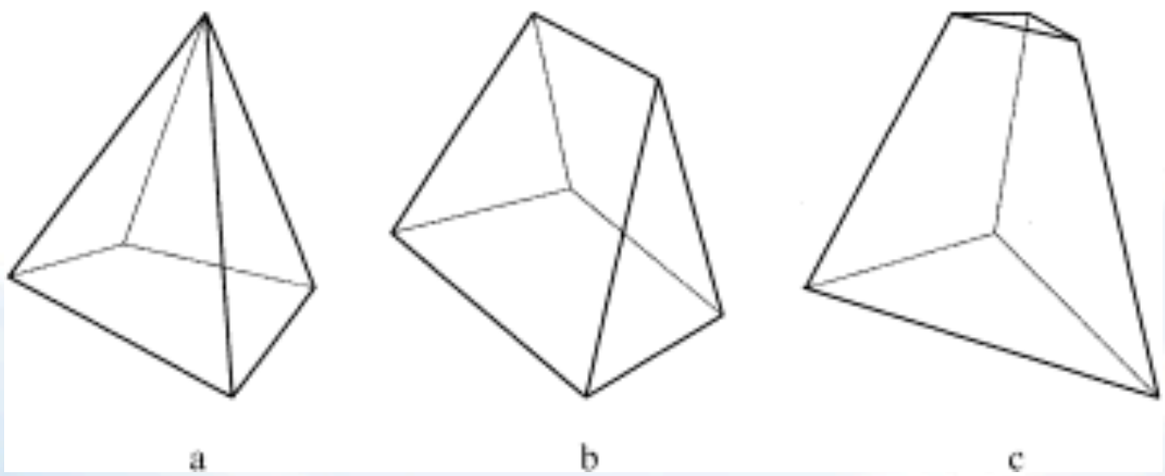
BH horizon acts like a perfect liquid;
BH destroys information as fast as possible. Why and how?

Study the dynamics of elements of empty space:
Strings in string theory; or polyhedra in loop quantum gravity

Dynamics of tetrahedron is regular and periodic

Chris Coleman-Smith

Phys. Rev. D87 (2013) 044047



Dynamics of pentahedra is irregular and chaotic

RHIC explores the most perfectly liquid, most opaque form of the quark-gluon plasma.

This discovery connects to the deepest properties of space and time

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This discovery connects to the deepest properties of space and time

But RHIC does not only probe Hot QCD Matter!

RHIC also probes "cold" QCD matter...

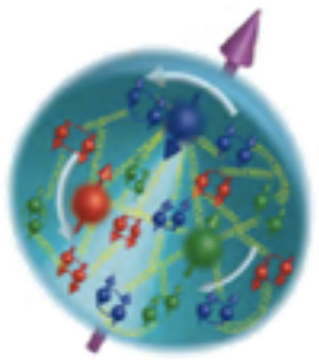
...in polarized proton-proton collisions

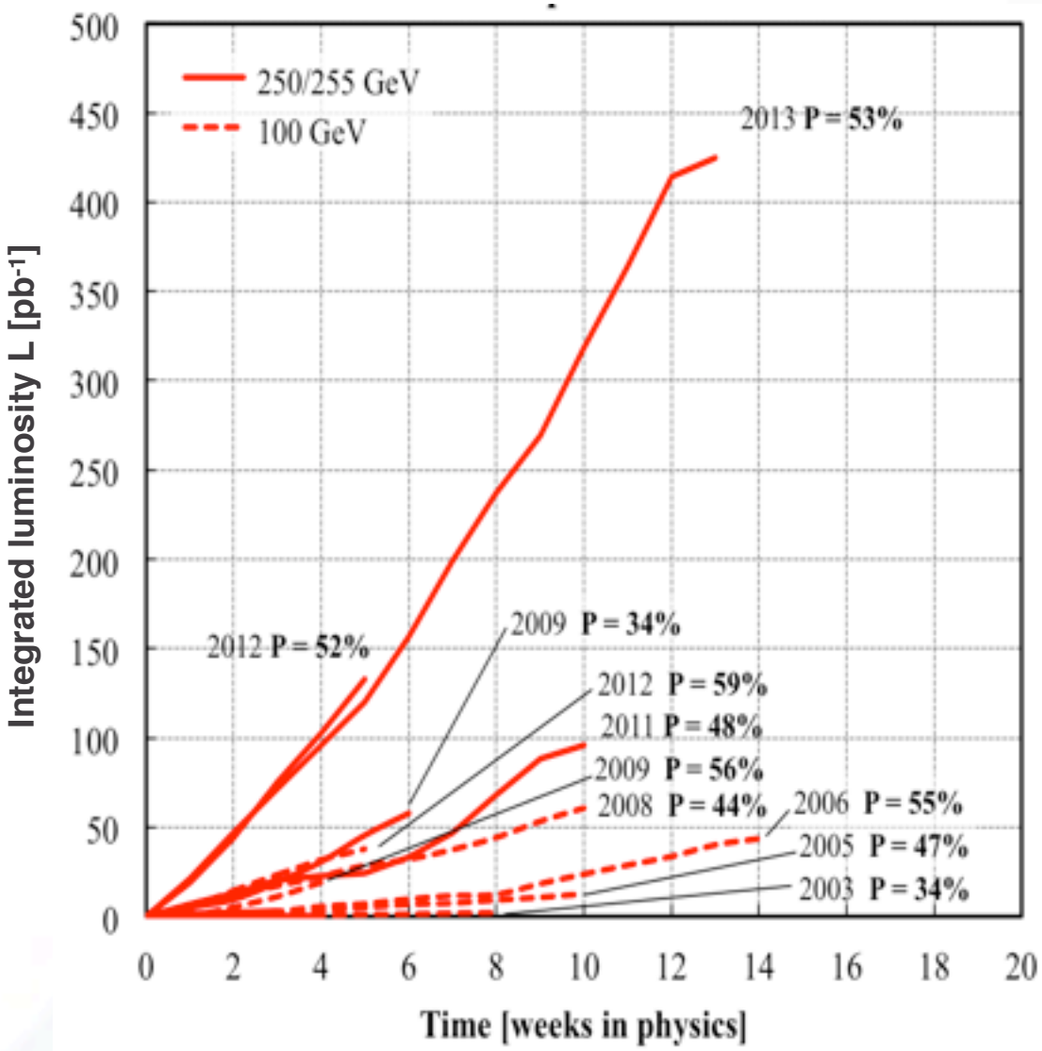
Finding the "Missing Spin"

- Run-13 completed 500 GeV polarized p+p with integrated luminosity of >400 pb^{-1} (20 trillion p+p collisions!)
- Achieved 2 NP milestones: Measuring sea quark and gluon contributions to proton spin

Spin of atoms resides in electrons and nuclei, not in the electric field. Is this different for protons?

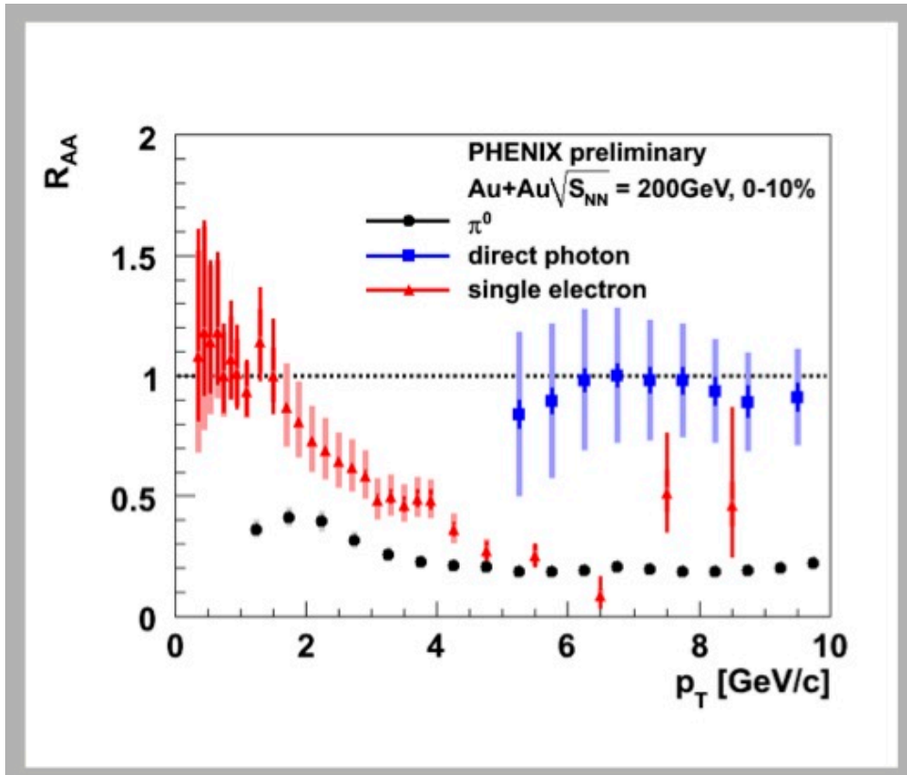
First indications from Run-12 are that 20% of proton spin resides in the gluon field. Run-13 will decide.

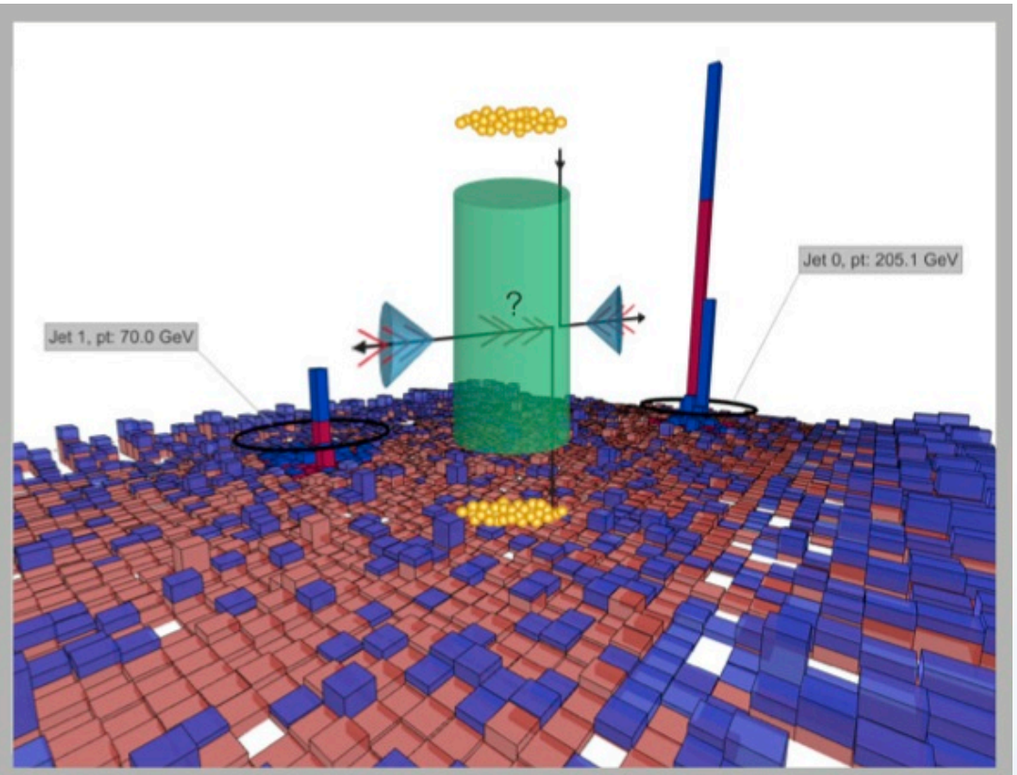




Precursor of the physics that can be done with much higher precision at an electron-ion collider (eRHIC) which will measure not just the total contribution of gluons to the spin, but provide complete images of the gluon distribution

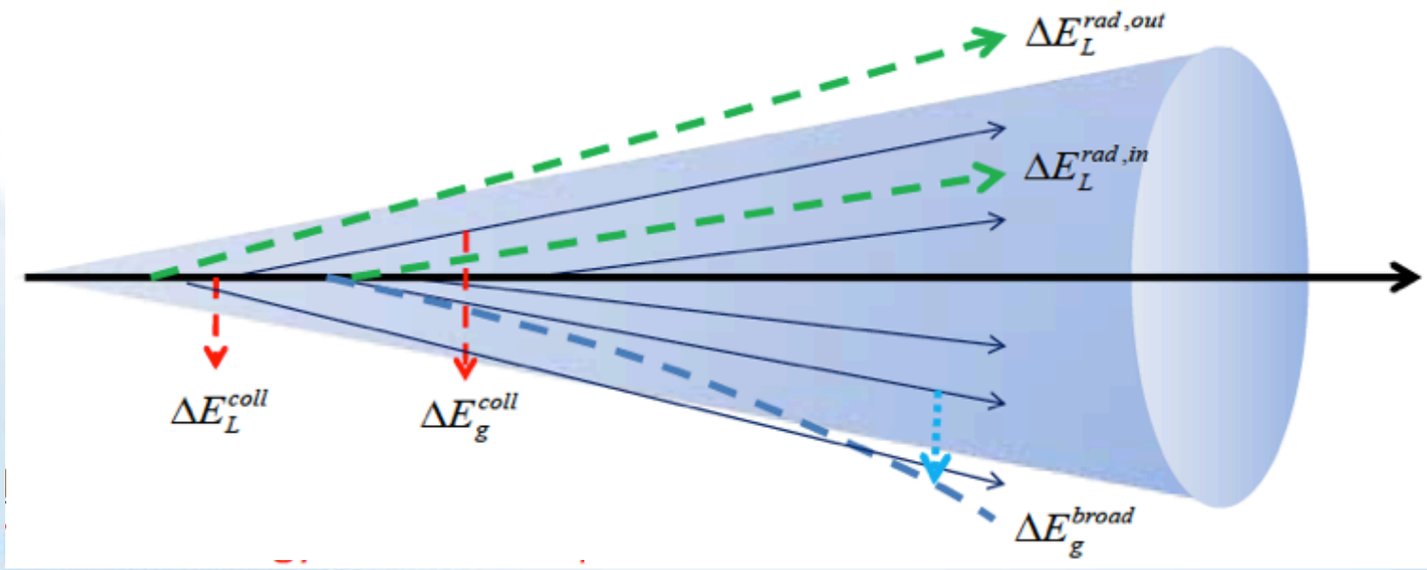
“External” probes of the liquid QGP





Jet quenching @ RHIC

Jet quenching @ LHC



Energy is lost by the leading parton in interactions with the hot matter, scattered out of the jet cone and absorbed

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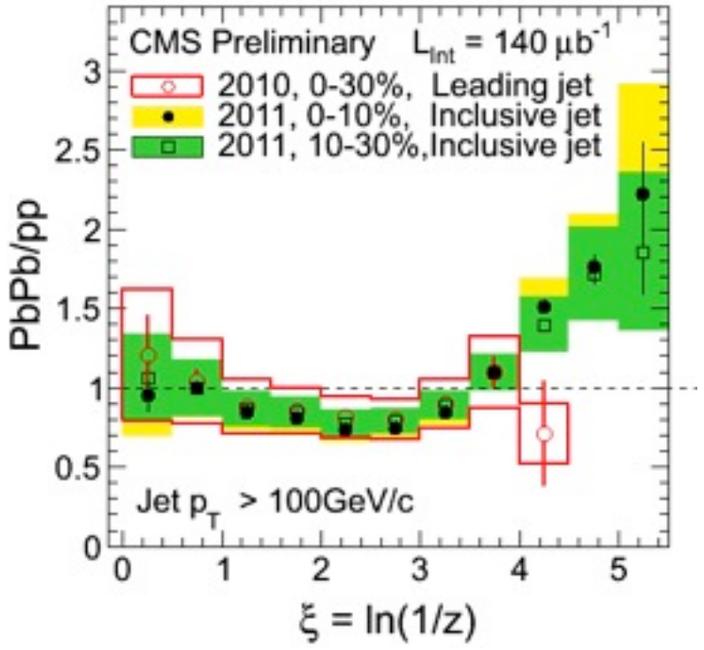
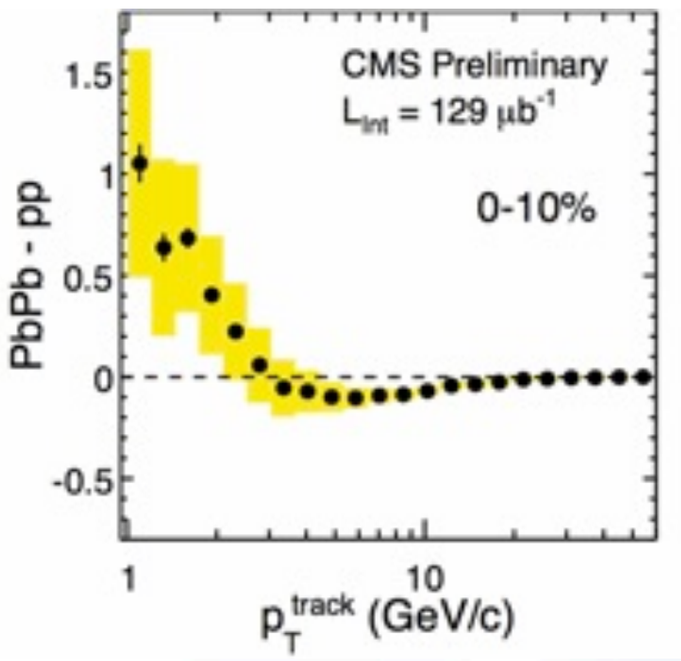
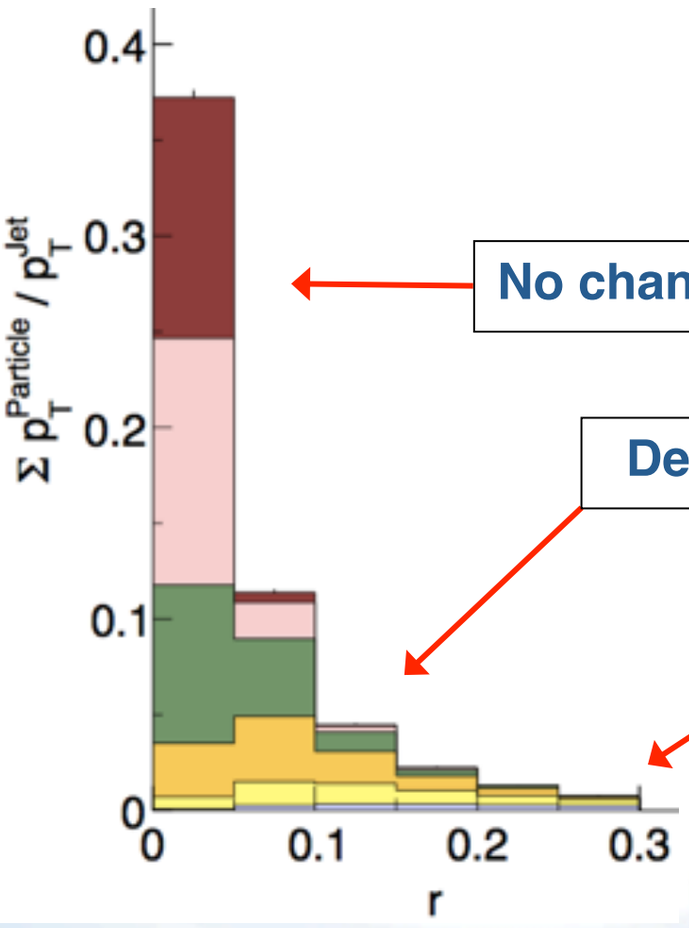
With a little help from your friends...

Jet quenching measurements at the LHC



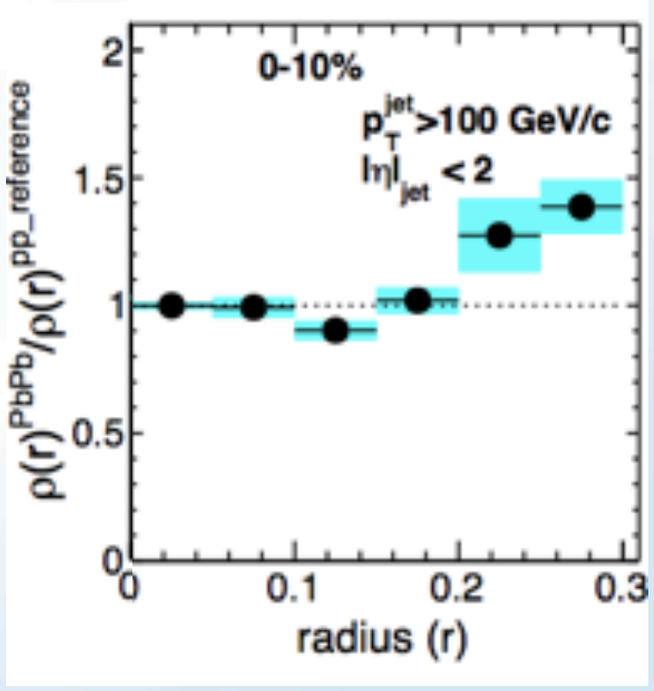




No change at small r, high p_T

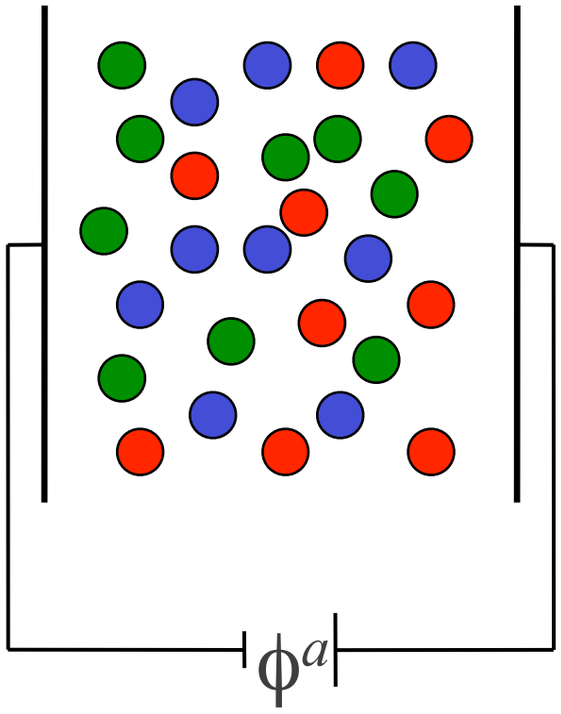
Depletion at intermediate r, p_T

Excess at large r, low p_T

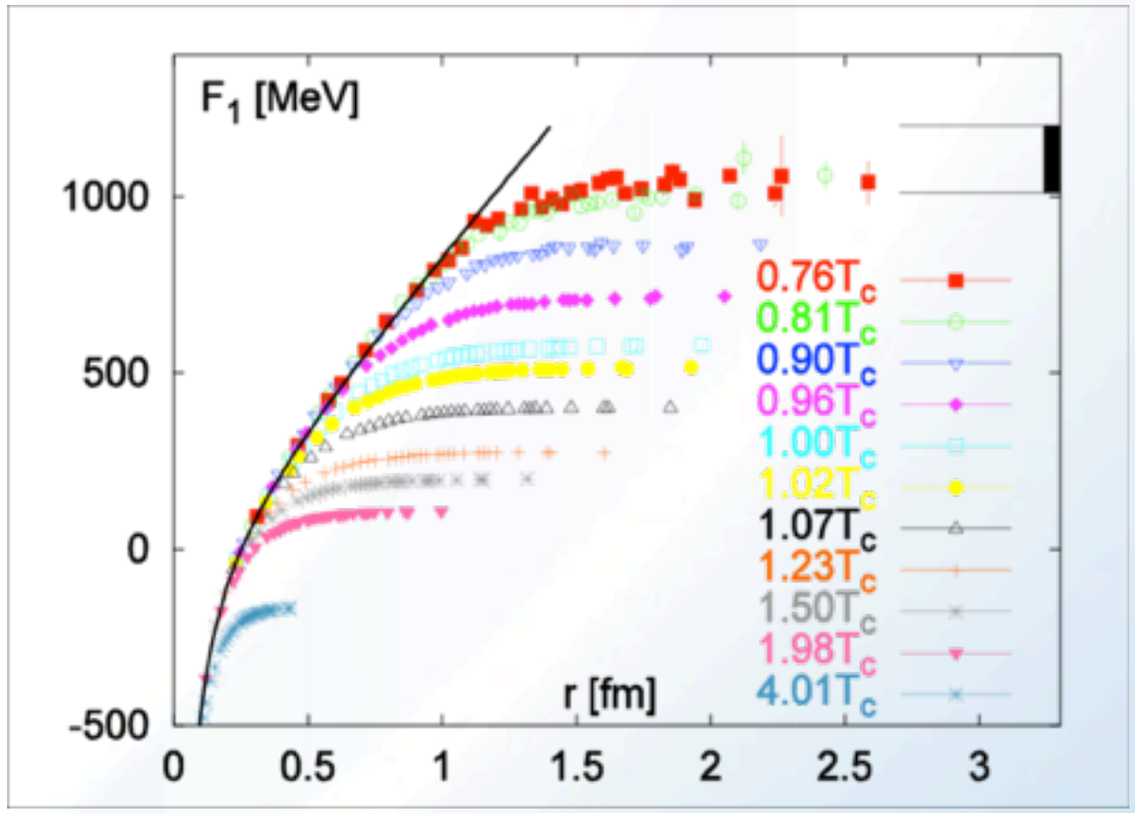


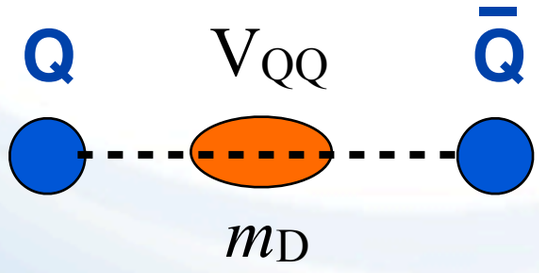
In the good old days...

... life for a heavy quarks in the QGP seemed so simple:
It was all about color screening



Lattice QCD





$$m_D \sim gT$$

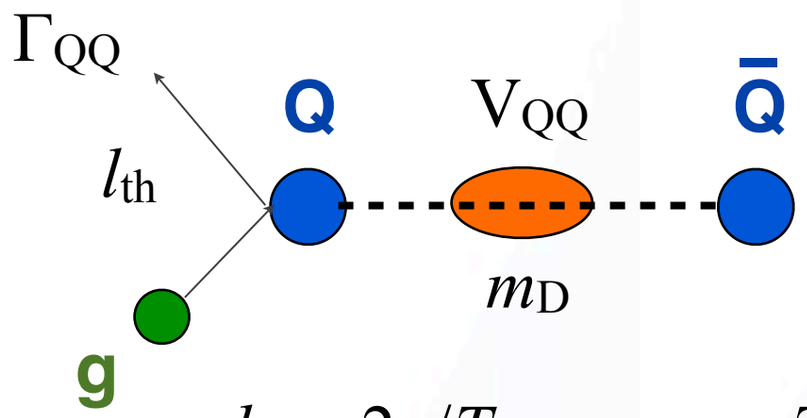
Only the data did not quite fit the theory!

We now know: The real story...

...is more complicated (as usual).

Q-Qbar bound state interacts with medium elastically and inelastically!

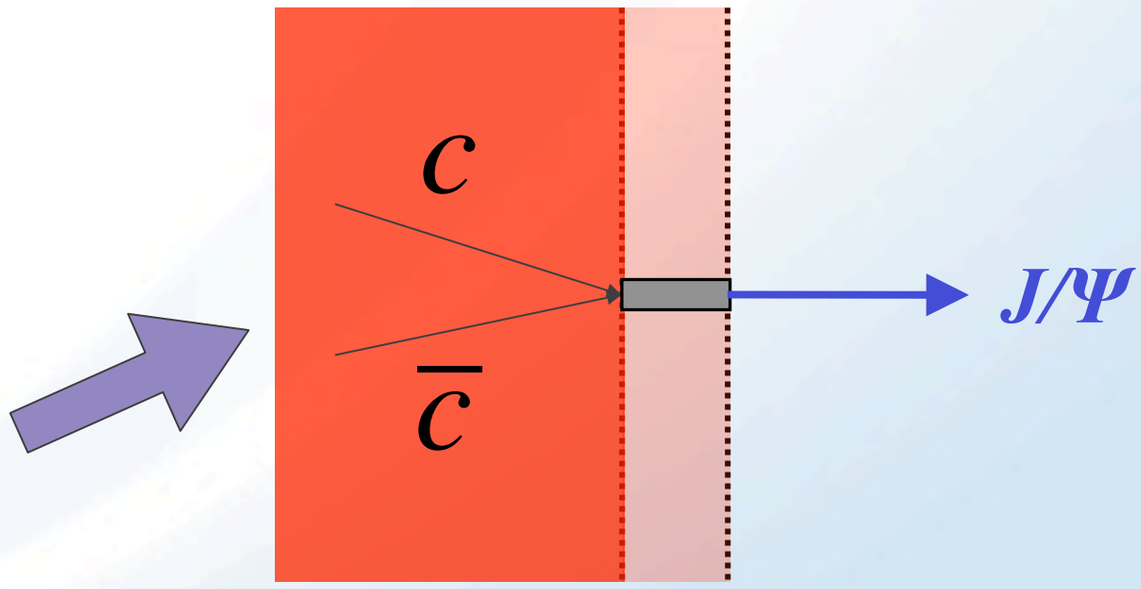
$$i\hbar\frac{\partial}{\partial t}\Psi_{Q\bar{Q}} = \left[\frac{p_Q^2 + p_{\bar{Q}}^2}{2M} + V_{Q\bar{Q}} - \frac{i}{2}\Gamma_{Q\bar{Q}} + \eta\right]\Psi_{Q\bar{Q}}$$



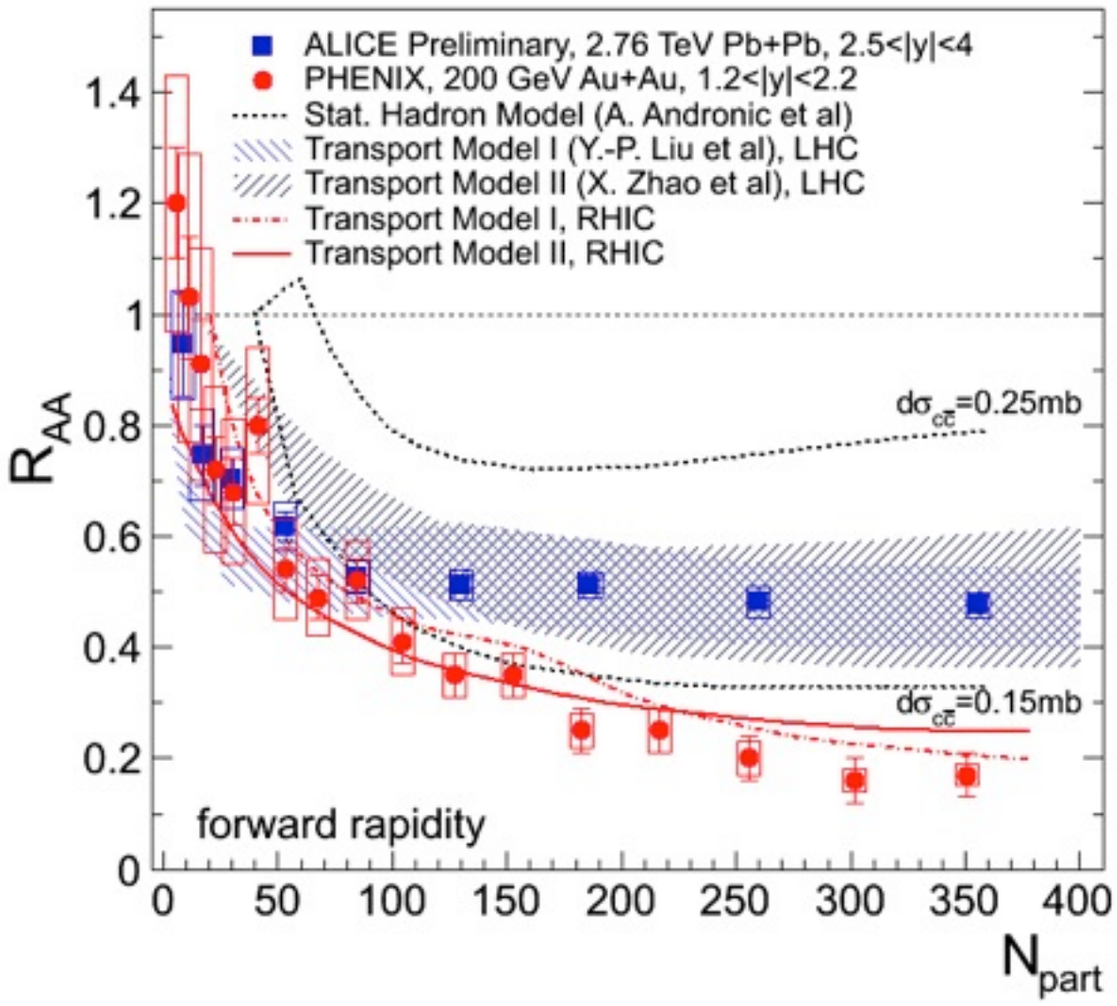
$$l_{th} \sim 2\pi/T, \quad m_D \sim gT$$

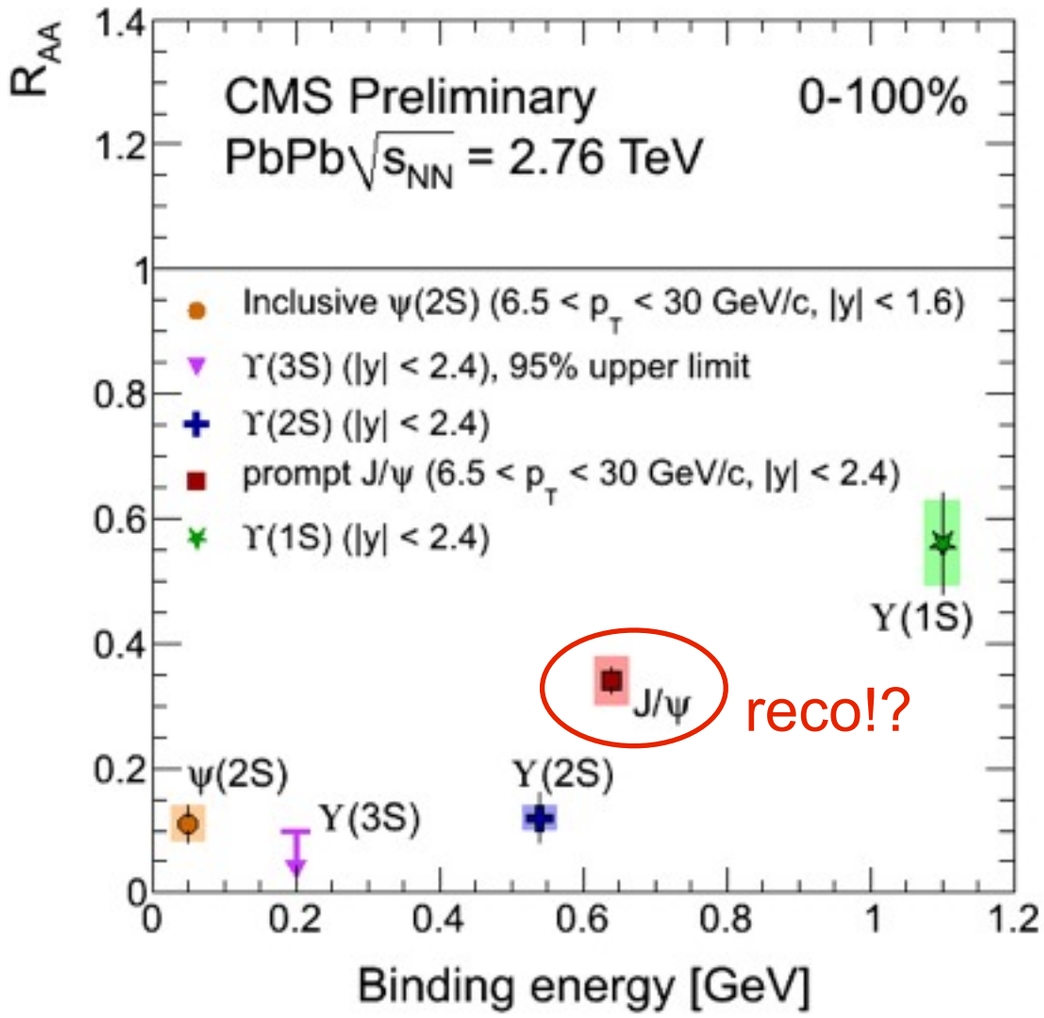
Heavy-Q energy loss and Q-Qbar suppression are closely related!

Recombination can also contribute when c-quark density is high enough!



J/ψ and Υ suppression





Less J/ψ suppression at LHC than at RHIC, at mid-rapidity and mid-forward rapidities:
c-cbar recombination explains data.

Full range of quarkonium states is becoming accessible @ LHC.

But we must not forget:

RHIC explores the most perfectly liquid, most opaque form of the quark-gluon plasma.

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New upgrades will make RHIC even more powerful:

Vertex detectors will identify heavy quarks

Electron cooling will increase luminosity

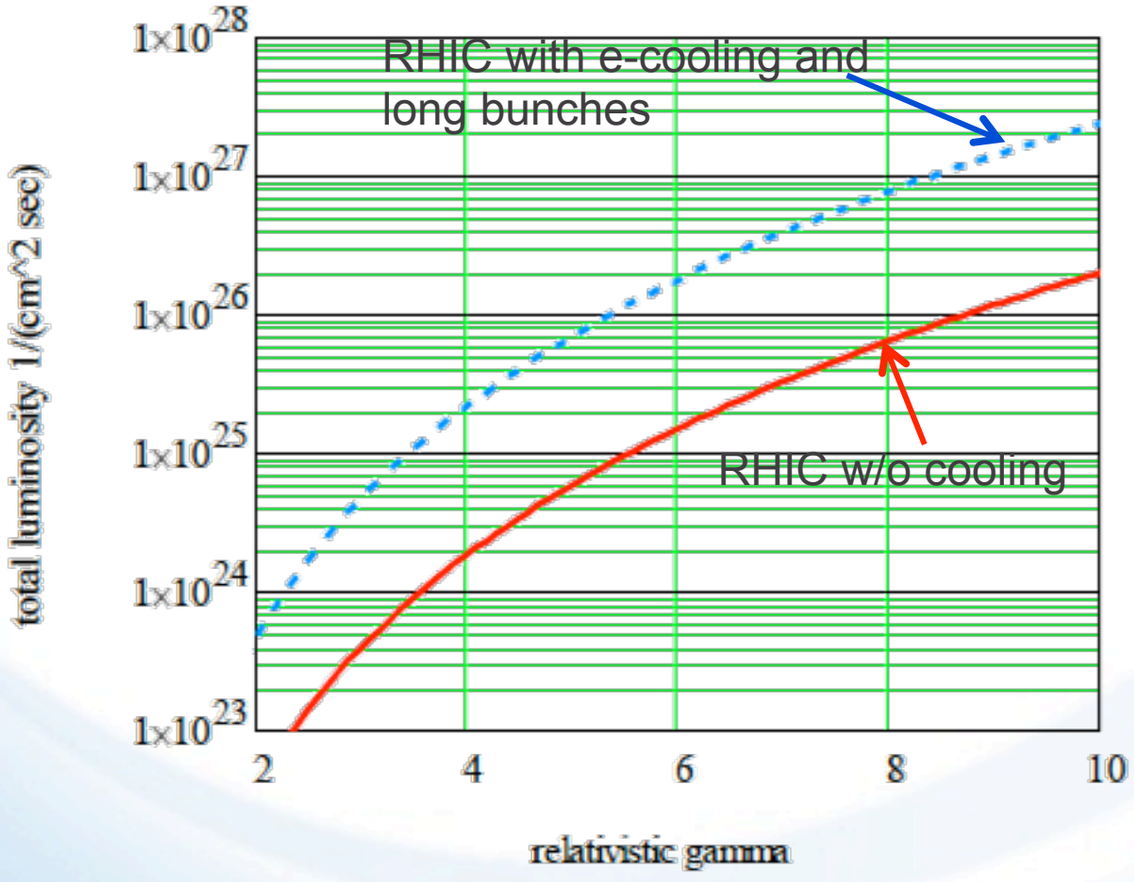
Investing in RHIC towards eRHIC

Machine Upgrades

- Bunched beam electron cooling; ~10x luminosity; ready after 2017
- Coherent e-cooling for p+p

Detector Upgrades

- STAR forward upgrade for p+A and spin physics
- STAR TPC pad rows
- PHENIX MPC-EX for forward p+A physics
- sPHENIX solenoid, EMCAL+HCAL for jet physics



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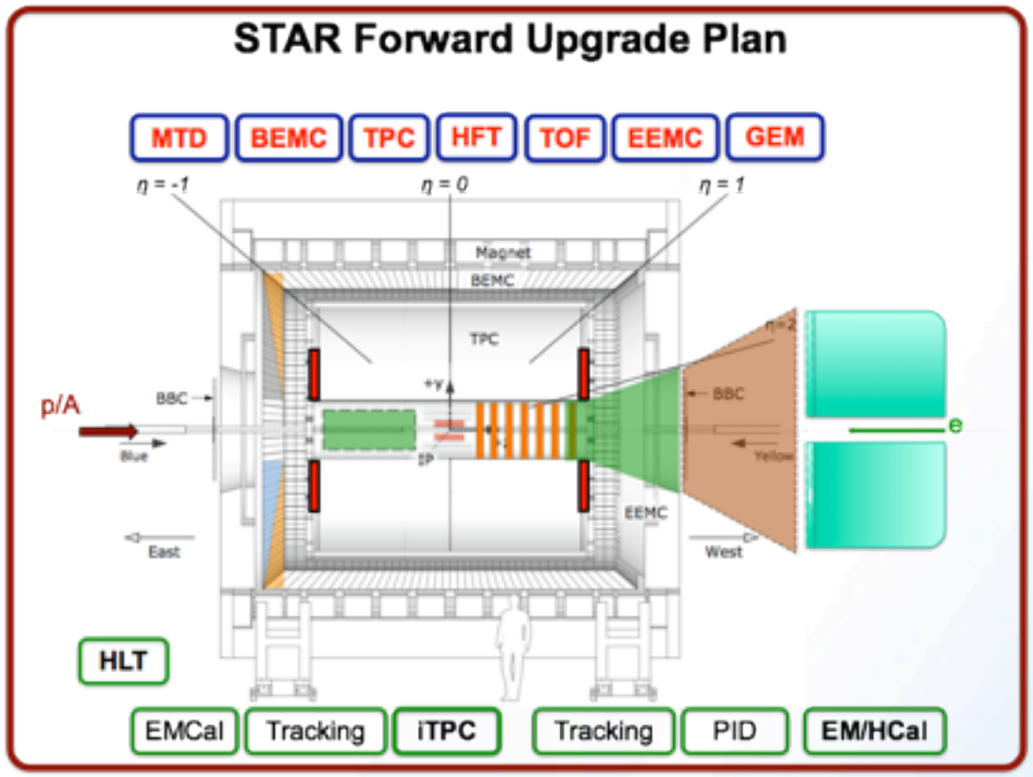
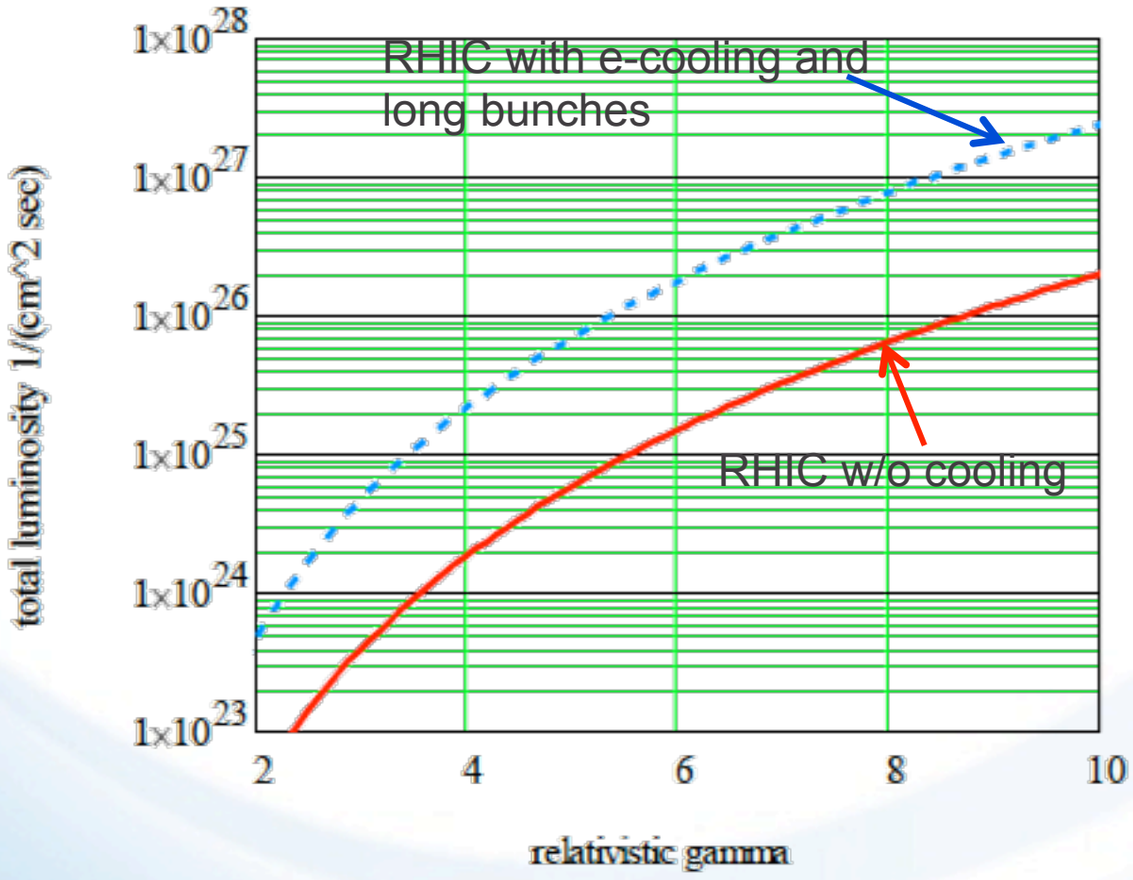
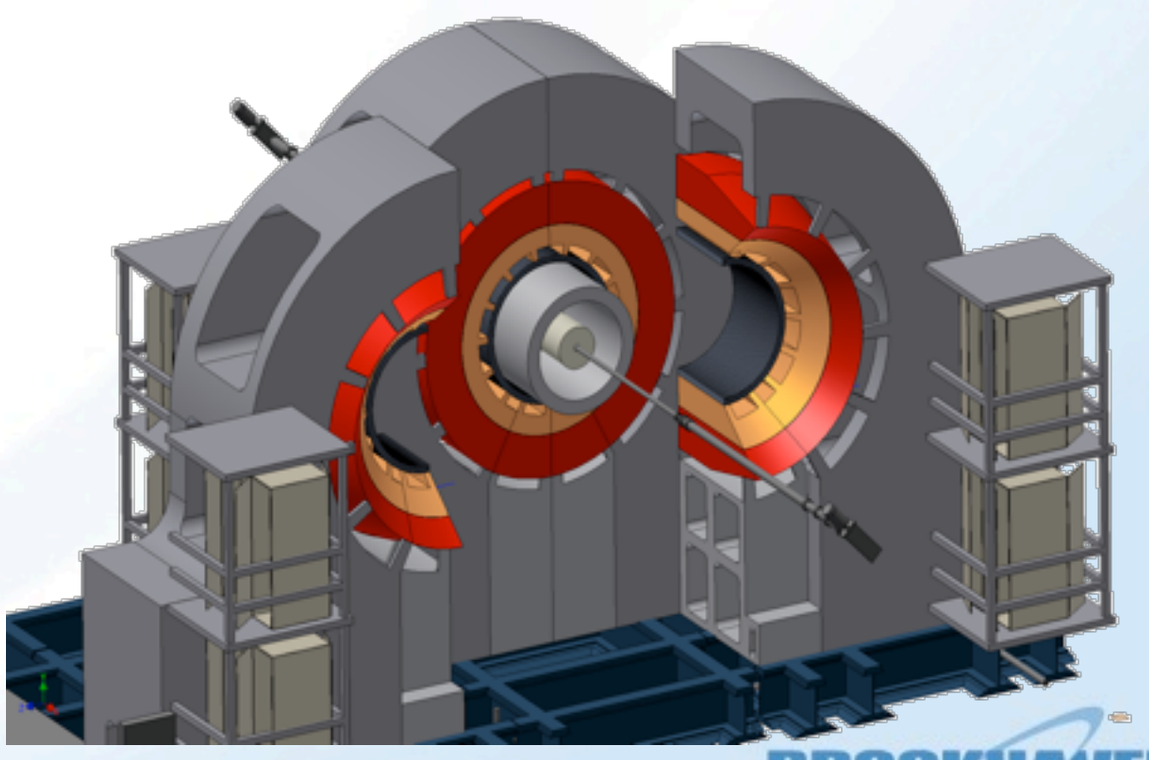
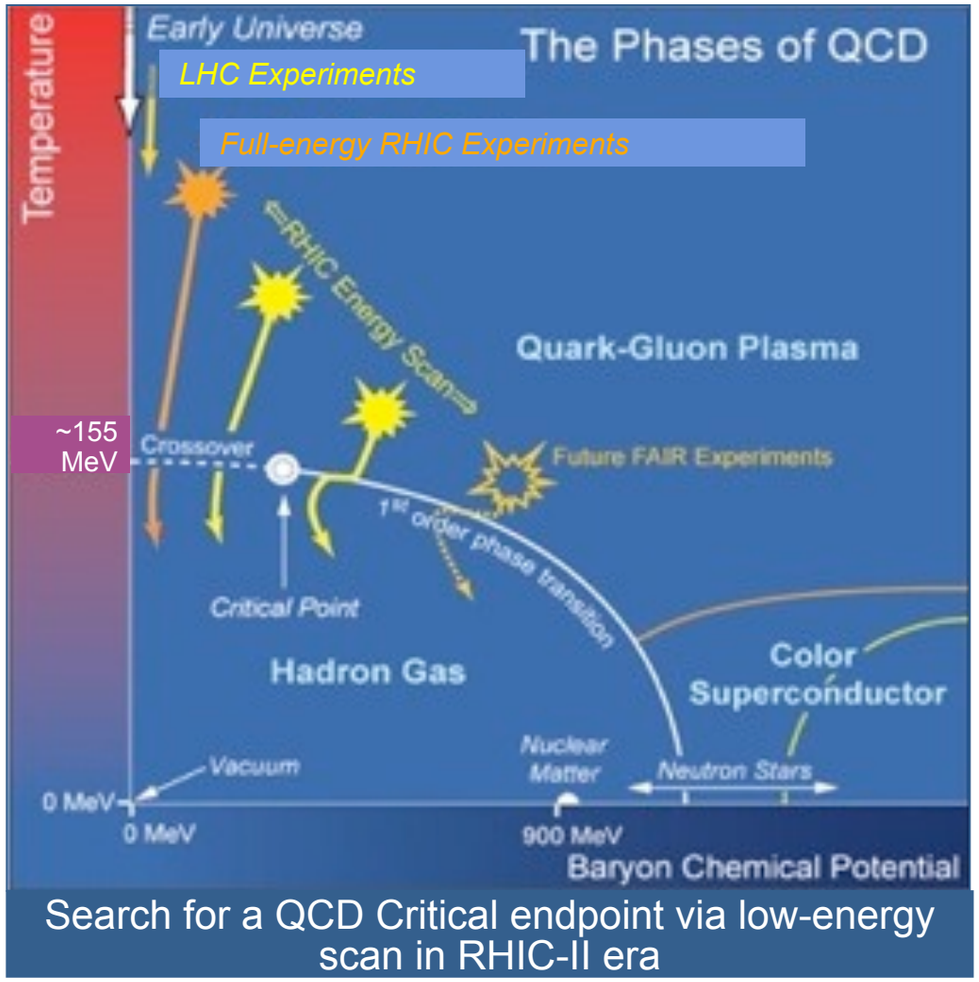






RHIC: Science Goals for the Next Decade

Quantify properties of the QGP by measuring heavy quarks and features of the QCD phase diagram as functions of temperature and net quark density.



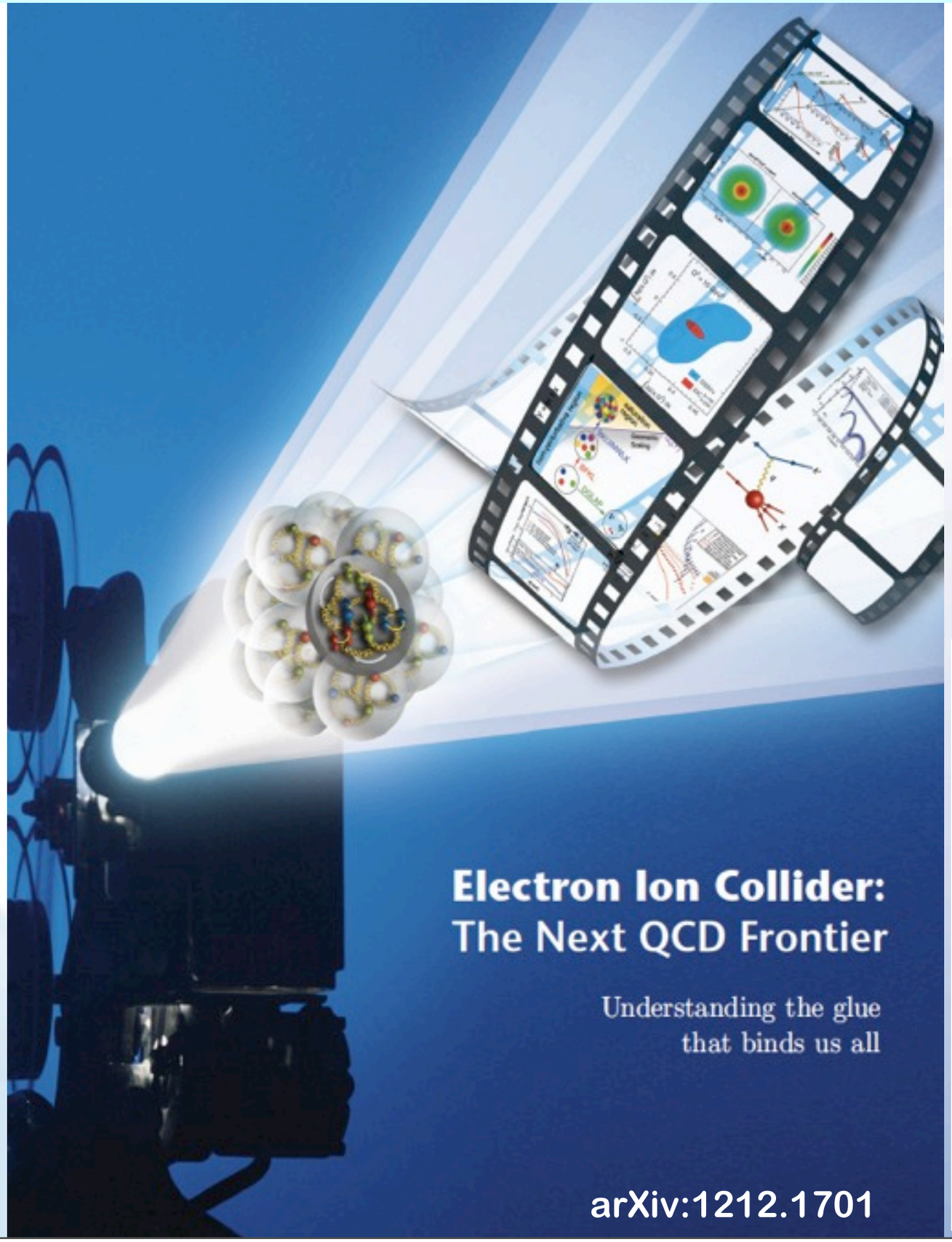
Search for a QCD Critical endpoint via low-energy scan in RHIC-II era

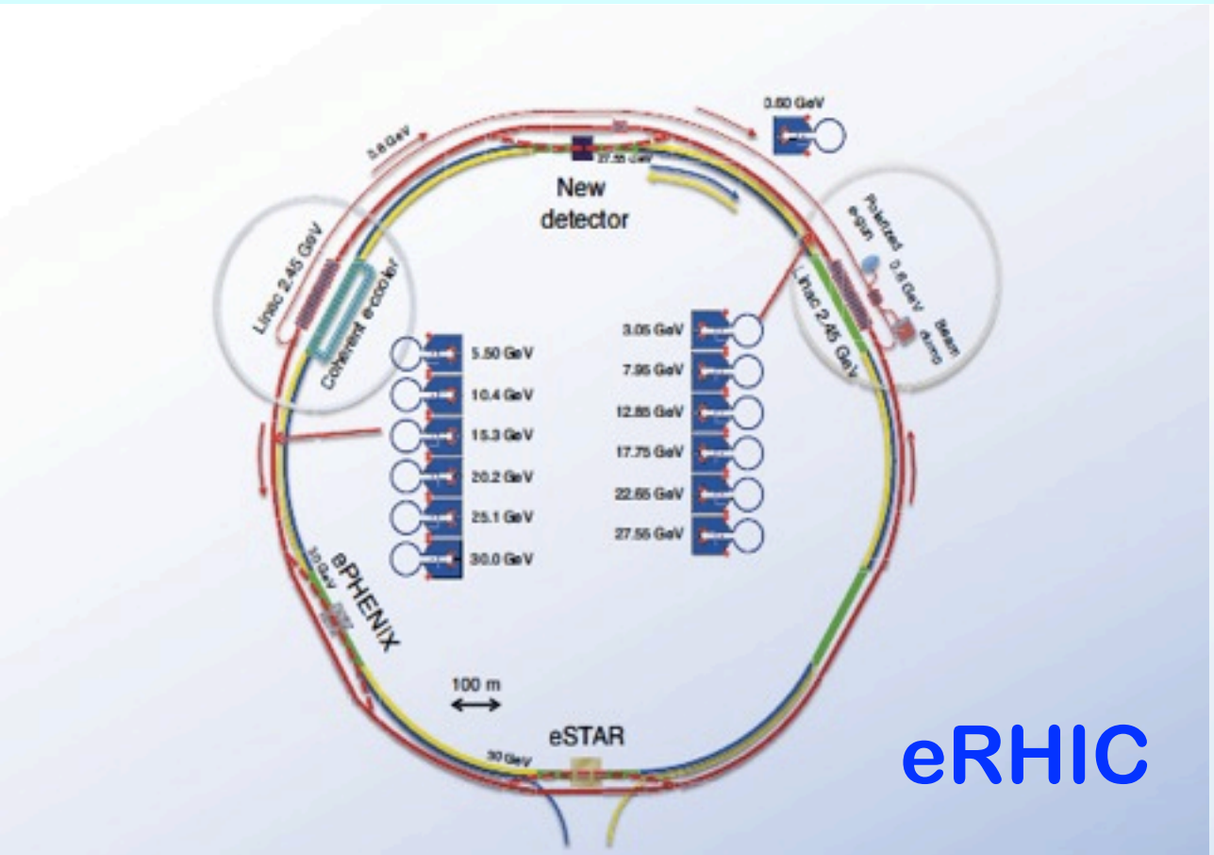
Exploit new discovery potential in searches for a QCD critical point and for the nature and influence of quantum fluctuations in initial densities and gluon vacuum excitations.

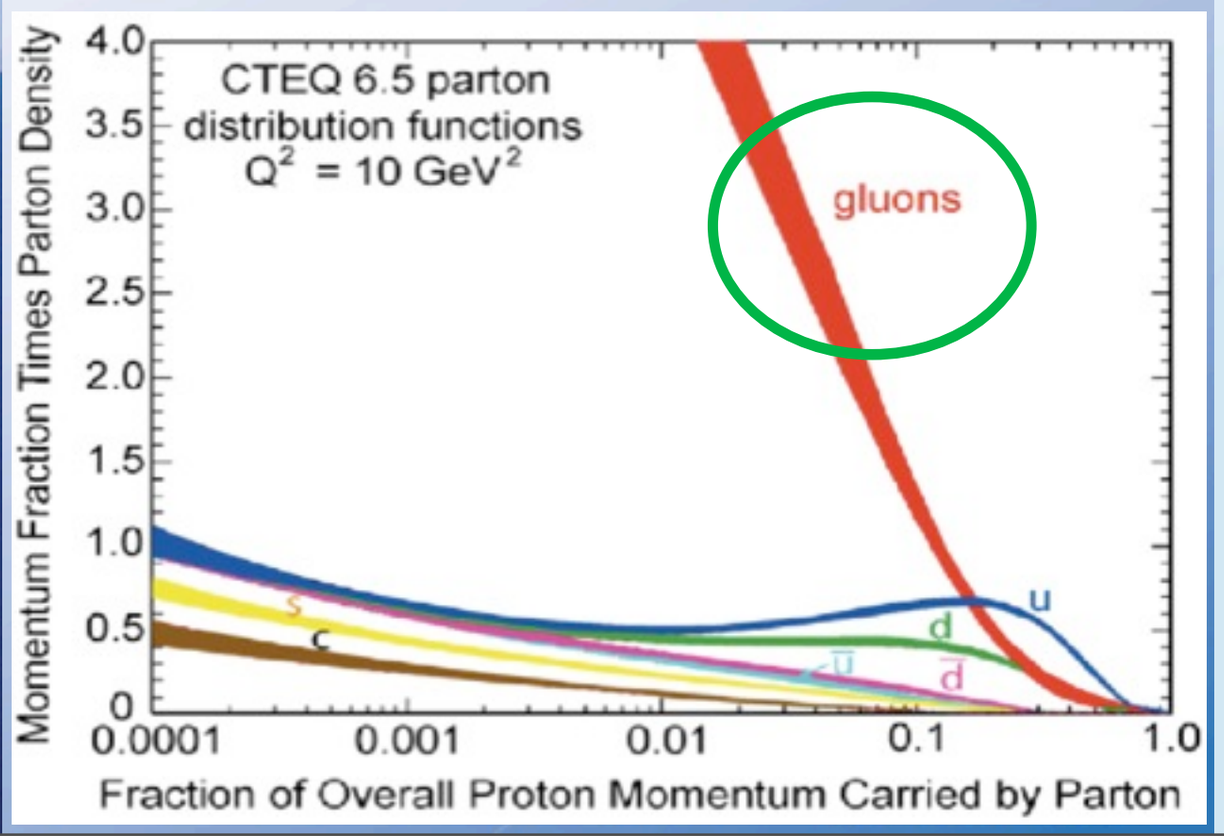
Continue explorations of the role of soft gluons in cold nuclear matter (gluon saturation, gluon and sea quark contributions to proton spin). Precursor to eRHIC program.

Caveat: Budget constraints make a deliberate execution of a decadal program of scientific inquiry challenging

EIC: An electron microscope for QCD matter

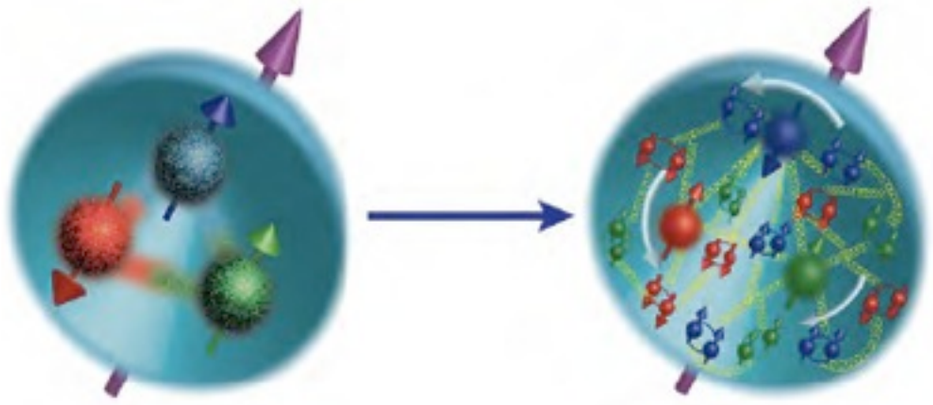






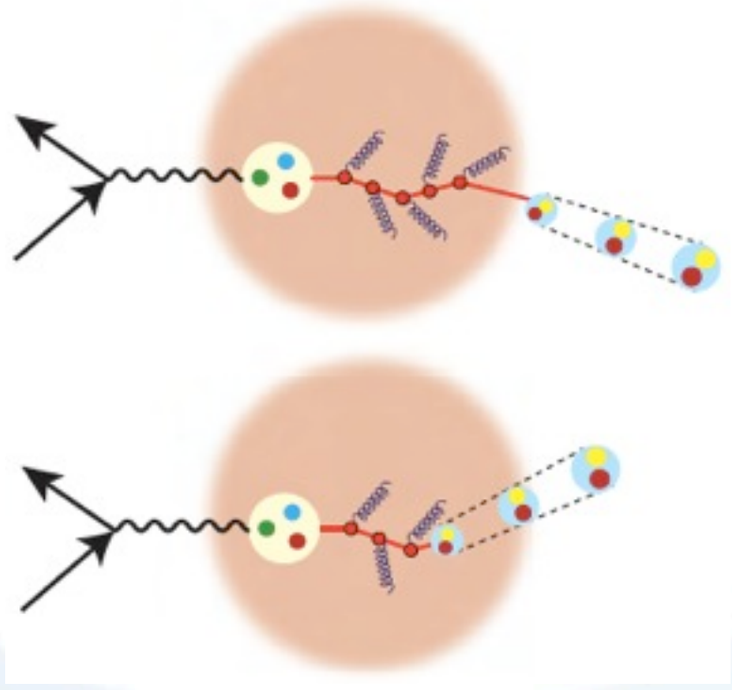
eRHIC will be a QCD laboratory

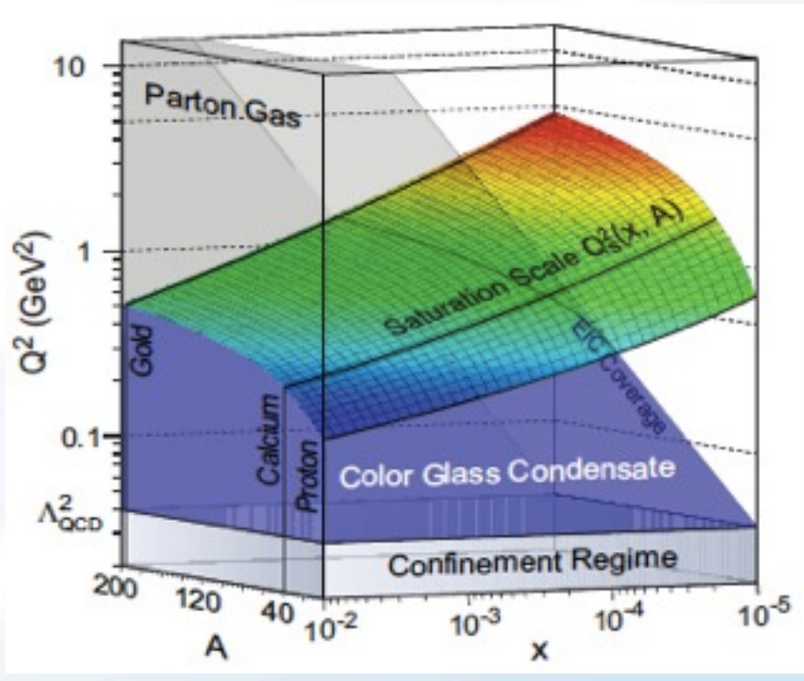
Gluon structure of proton



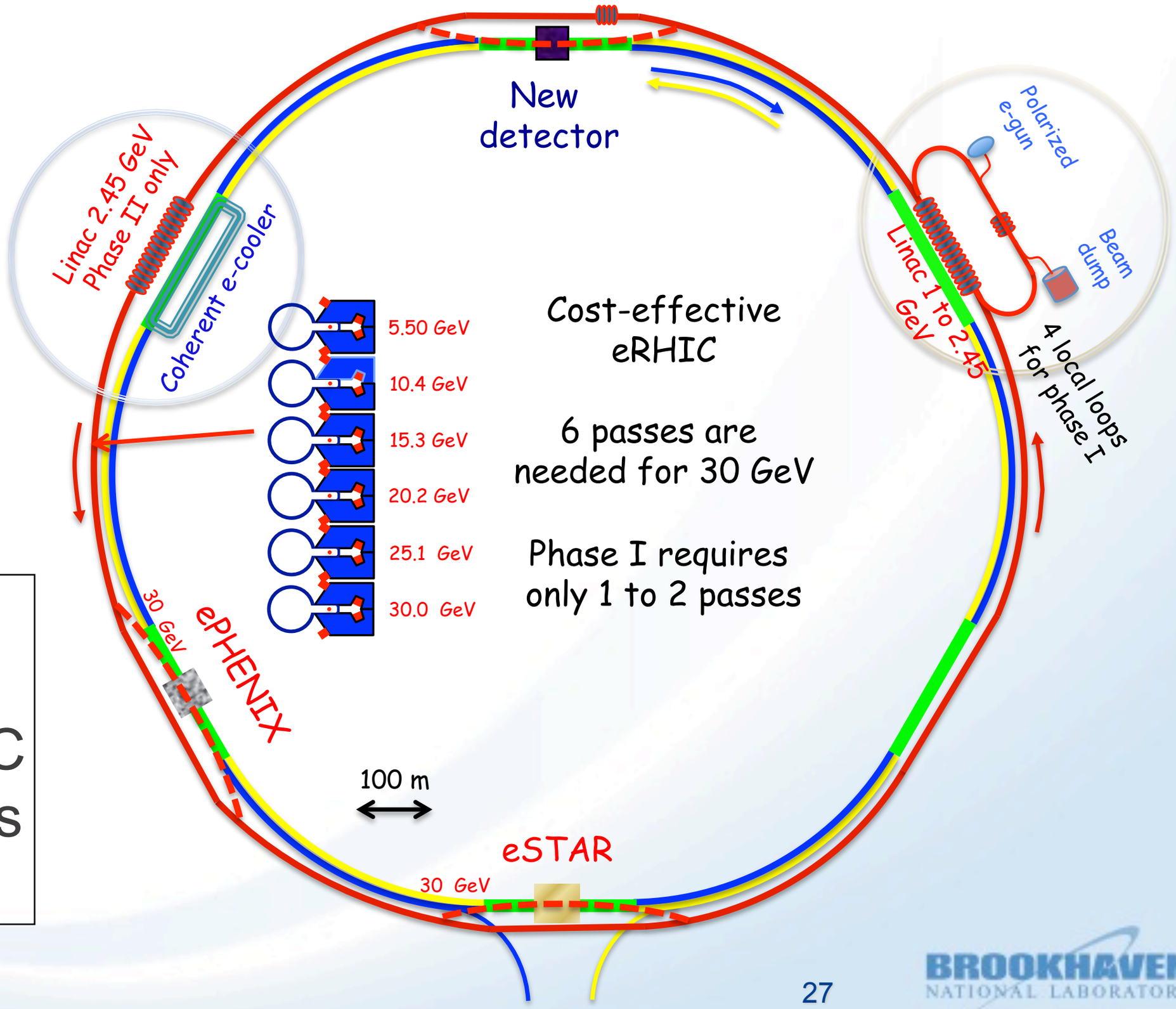
Microscopic processes studied in bulk at RHIC

High density phase of gluon matter (CGC)





From RHIC to e-RHIC



Goal:

First e-RHIC experiments in 2024/25

Summary

- If RHIC did not exist, it would need to be built
- $2B infrastructure uniquely capable of exploring QCD matter in the perfect liquid domain
- RHIC sits at the sweet spot: most liquid & opaque QGP
- The discovery potential of RHIC is undiminished
- RHIC-2 exists now -- even higher luminosity in 2017/18
- RHIC's path toward eRHIC is clearly delineated and provides for a cost-effective realization of the EIC
- We are developing the technical and scientific case for eRHIC to be presented at the next long range plan
- RHIC & eRHIC can extend U.S. preeminence in research on QCD for the next 2-3 decades

If you want to know more...

Hot and Dense QCD Matter

A Community White paper

http://www.bnl.gov/npp/docs/Bass_RHI_WP_final.pdf

The Exploration of Hot Nuclear Matter

B.V. Jacak and B. Mueller

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